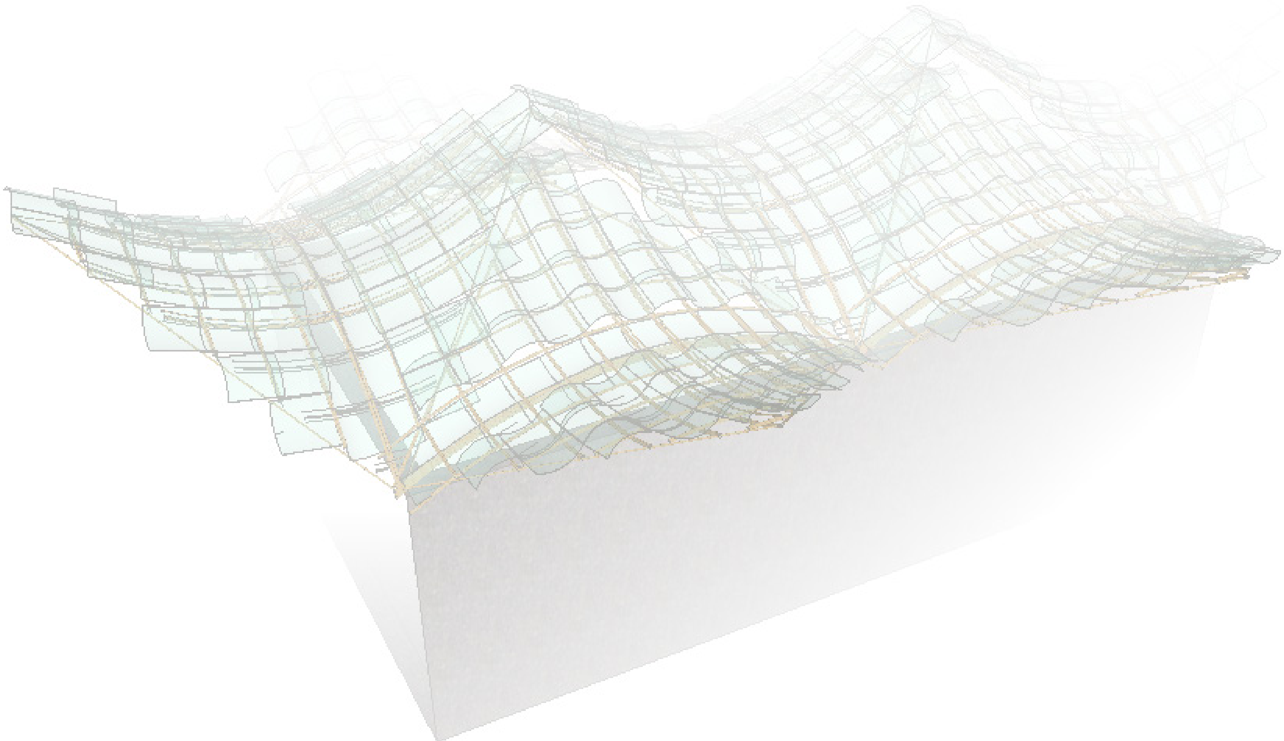
BAMBOO AND THIN GLASS

STRUCTURAL ANALYSIS OF BENDING BAMBOO AND THIN GLASS FOR GRIDSHELLS



RESEARCH REPORT

MSC. BUILDING TECHNOLOGY,
FACULTY OF ARCHITECTURE, URBANISM AND BUILDING SCIENCE

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ACKNOWLEDGEMENT

Last two years of my master's programme has been a great journey. Being an international student, the exposure I received was very different from my home country, India. In Delft University of Technology things operate in a different manner. And I took some time to get used to this system. The exposure at TU Delft has not only helped me to progress in terms of education, but also has been influential in overall development. Most importantly I have learnt to express my ideas and design eloquently. This is very essential for an architect.

For my master's thesis project when I had to select a topic I knew I wanted to do something with glass. This inspiration came from the structural course I had taken in my first year. I cannot thank Fred Veer enough for encouraging many fellow students and me. We developed interest in this material during this course. So in my summer break I had already started thinking of different aspects of glass as a construction material. But I always had an affectionate towards natural materials. Coming from a tropical country, I have seen a lot of bamboo construction and always dream of living in one. Unfortunately these bamboo houses are considered as "kutcha" or temporary construction. Hence I took this opportunity to use bamboo with glass to enhance the material leading to "pukka" or permanent construction.

Having said this, there are a lot of people involved who helped me to make this project viable. First of all I would like to thank Fred Veer. Without his support, I would not be able to reach at this stage. He always encouraged me to go ahead with my decisions. Even though with his busy schedule he has taken time out to perform experiments with bamboo. His teachings is very valuable and will stay with me for rest of my life.

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I would also like to thank Frank Schnater and Christian Louter for the valuable feedback they have given me for this project. Even though there were few differences in opinion, their experience and critical view has helped me to develop this project.

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LIST OF SYMBOLS

κ = curvature of the beam
κ_1 = first principle curvature
κ_2 = second principle curvature
κ_g = Gaussian curvature
σ_n = normal stress
σ_m = bending stress
σ_{max} = maximum pricipal stress
M = bending moment
E = modulus of elasticity
I = moment of inertia
W = moment of resistance
R = radius of curvature
Δ_x = deflection in horizontal x-axis
Δ_z = deflection in vertical z-axis
l_o = outer length of a curved beam;
Δl_o = change of outer length of a curved beam;
l_i = inner length of a curved beam
μ = frictional coefficient
τ_f = frictional torque
R_d = distance between center of rotation
F_g = reaction force of thin glass
F_w = wind force
FEM = finite element method
FEA = finite element analysis

INTRODUCTION

1

Bamboo can be used structurally, if engineered properly and can compete with other modern materials like steel, concrete, wood and glass. But unfortunately its use is limited to furniture, temporary structures and scaffoldings. Firstly, it is very light in weight. This helps to design a low weight structure that is good for resisting dynamic influence.

Bamboo has not yet been accepted as a construction material due to lack of consistency. A structure or a building is made up of combination of different materials like glass, concrete, steel, wood; each material performing a specific role. Most widely used building material, reinforced cement concrete is used for columns, beams and slabs. The steel bars transfers the forces in tension and concrete acts in compression. There is an interesting concept which is exploring bamboo reinforced concrete, acting similar to steel reinforcement. Hence bamboo has the potential to serve as an alternate sustainable building material. By integrating bamboo with a high-tech material, can be a way of making bamboo more relevant in the construction industry. Hence the drawbacks of one material can be countered by other material. The question rises how to deal with irregularity and durability issue of bamboo. After combining with other material the next step would be to engineer the bamboo joints and have a sophisticated connection system.

In this thesis report bamboo is combined with thin glass. Thin glass is widely used in electronic products, it is still finding its way for architectural purpose. The main purpose of this research is to increase the serviceability of bamboo structure and also explore the possibilities of thin glass.

1.1 WHY GLASS AND BAMBOO?

With rise in global world population, increases the demand for development and re-construction. The construction of buildings and structures using modern materials like steel and concrete is not only uneconomical but also leads to increase in greenhouse gases. This reflects the consumption of fossil fuels. The building sector accounts for nearly half of the total energy consumption. This means there is something wrong with the way buildings are designed, built and operated. One of the key factors while designing a building is selection of materials (figure 1.1a). Depending on the boundary condition (site context), material selection should be the driving factor. If correct materials are selected based on the function and need of a particular building, lighting, heating and cooling demand will reduce. This will in turn reduce emissions to a great extent.

Figure 1.1a: Bamboo canes.

Most material selection ignores impacts of manufacture, maintenance and disposal. Metal concrete and plastics are materials causing air pollution, water pollution and greenhouse emissions. As seen in figure 1.1b, wood construction has the lowest impact on the environment. However, another natural material, bamboo, is stronger than wood has not been explored to its full potential. Bamboo can be the next generation of timber. Compared to timber bamboo grows faster and captures 4 times carbon dioxide as timber. It can grow up to 30m within 6 months. Hence the annual yield of bamboo plantation will be more than wood. Apart from its growth rate, its mechanical strength is better than most of the wooden species (figure 1.1c)

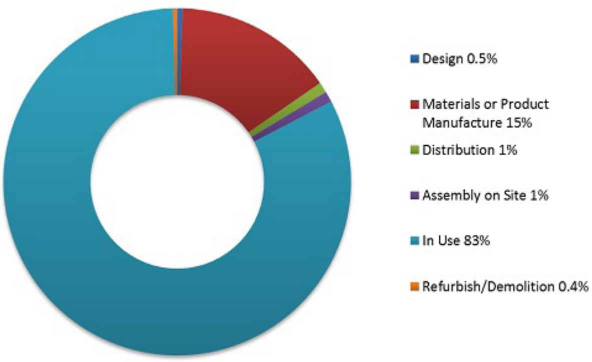


Figure 1.1b: Percentage of greenhouse gas emission in construction sector.
ref: ("Embodied Energy and Carbon", 1999)

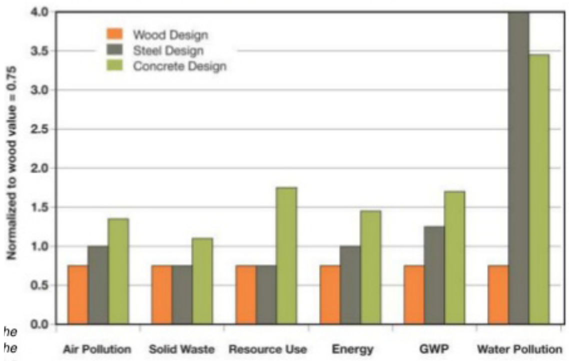


Figure 1.1c: Comparing environmental effects by using different material for construction.
ref: Data compiled by the Canadian Wood Council

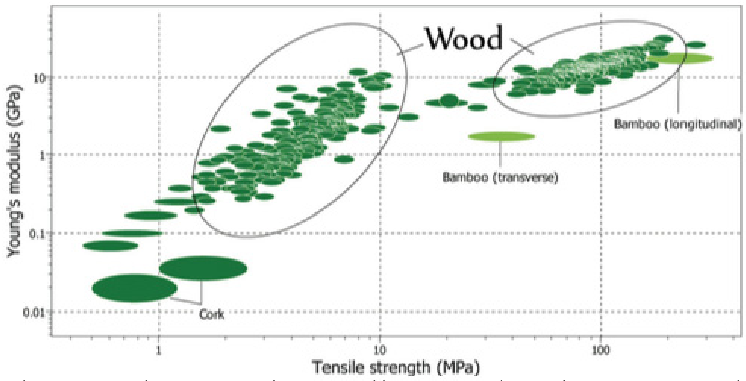


Figure 1.1d: Comparing tensile strength and young's modulus of natural materials

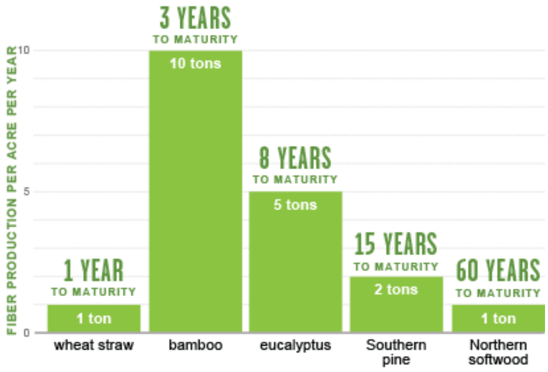


Figure 1.1e: Rate of growth of different species of grass.
ref: ("Kimberly-Clark Sustainability Report 2012", 2012)

Thin glass contributes in maintaining the structure lightweight. Although glass is not a natural material, but if used appropriately with regards to site context and function of the building, can contribute to save energy. There is a wide range of cladding materials available in the market. But most of them are in form of panels and the sizes are factory or company fixed. Custom sizes are possible but turn out to be expensive. However, it does not give freedom for architects and designers to explore free form geometry, as each panel will have different shape and sizes. To clad such structures, different moulds are required for each panel, which is not feasible. With the invention of thin glass, which is flexible without compromising on its strength, a single sheet can be deformed in many ways as per the design. If designed and detailed properly, there is no further maintenance required. Compared to normal glass panel the density of thin glass is so less, thus using minimum material in construction is also a sustainable technique.

At the end of life, glass is fully recyclable to form new glass panels. Broken glass chips can be melted and used in the mixture which forms molten glass. This helps in saving significant amount of natural raw material. By adding recycled glass, it helps in saving energy while production of new glass. As the cullet melts at a lower temperature compared to raw materials.

Unlike polymers, it does not heat so easily if used in hot climatic conditions. Generally roofs clad with polycarbonate sheet have low thermal resistance and start giving out odor at high temperatures.

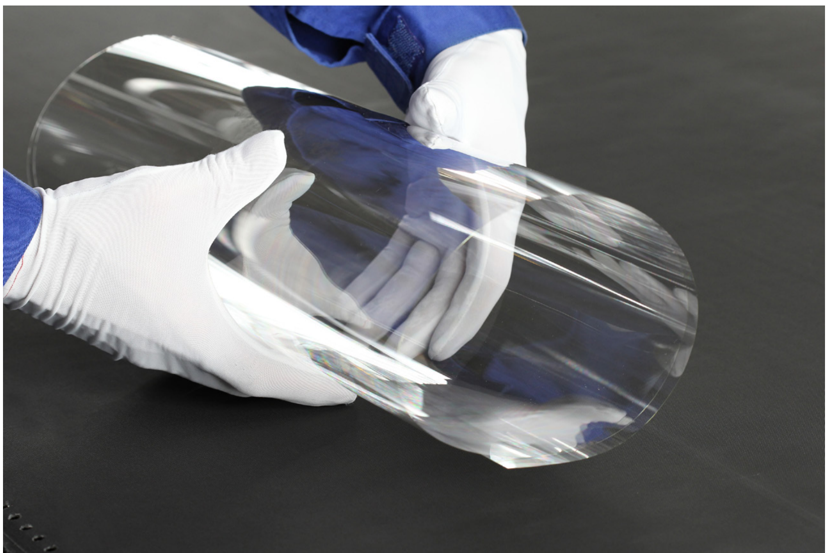


Figure 1.1f: Thin glass

	THIN GLASS	POLYCARBONATE
STRENGTH	200 MPa	70 MPa
WEIGHT	2.48 g/cm³	1.15 g/cm³
TRANSLUCENCE	TRANSPARENT	TRANSPARENT
FLEXIBILITY	COLD BENDING	MOLDED
TEXTURE	REGULAR	REGULAR
HARDNESS	595 HV	6 HV
ACOUSTICS		
ODOR		HIGH TEMPERATURE
FIRE RESISTANT	NON FLAMMABLE	SELF EXTINGUISHING
THERMAL RESISTANT	1 m.C/W	5 m.C/W
WEATHER RESISTANT		
SCRATCH RESISTANT		
CHEMICAL RESISTANT		
RENEWABLE		
RECYCLABLE		

* All the values and data obtained from CES edupack by Granta

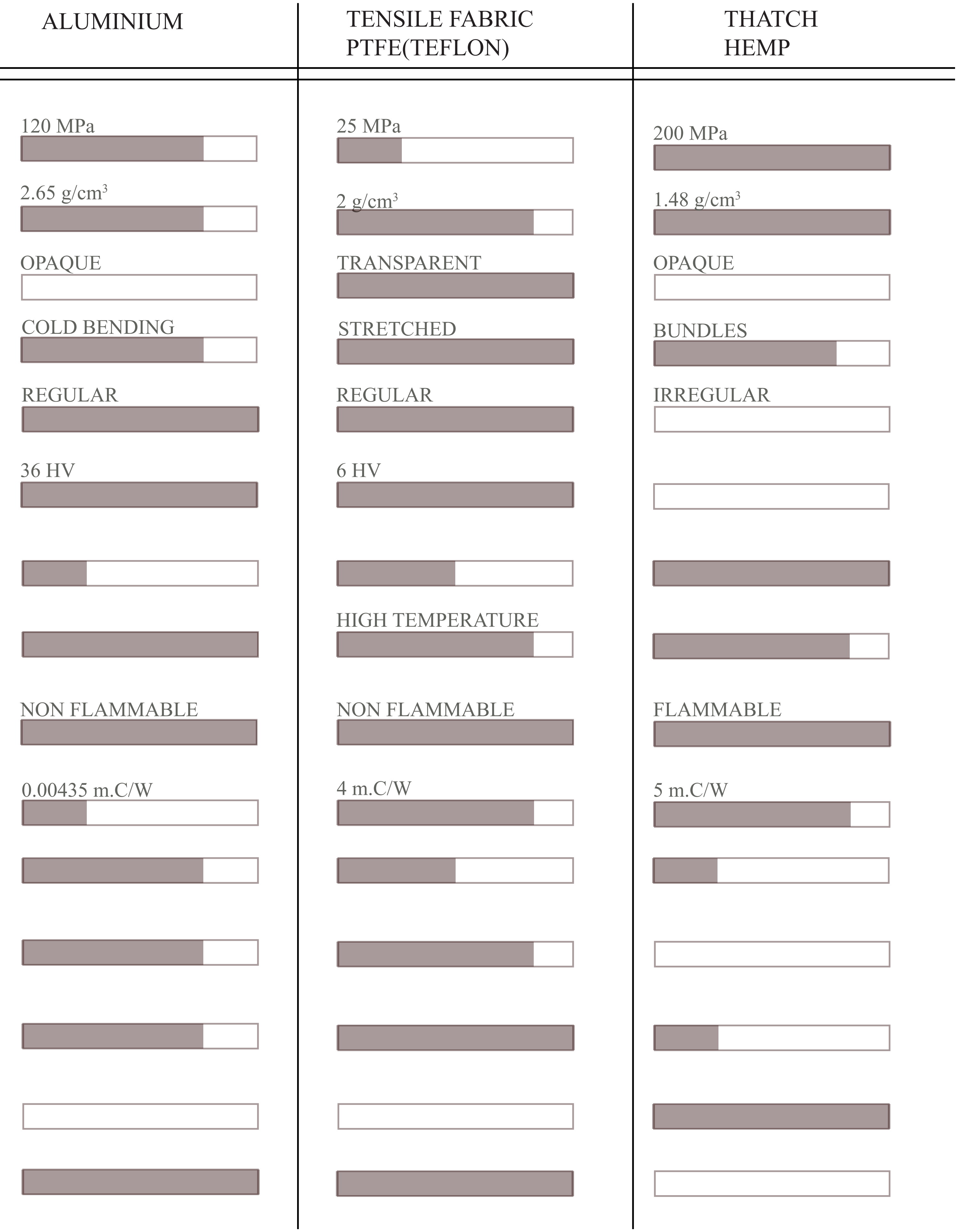


Figure 1.1g: Cladding options and comparison

1.2 RESEARCH GOALS AND LIMITATIONS

Shell structures are very popular amongst architects and engineers. Earlier, only concrete shells were developed. The disadvantage of using concrete is, it is labour intensive and not economical. For formwork of concrete shell wooden laths are used and removed once cured. This is not a sustainable technique. Hence alternate materials should be explored to develop a shell structure. In recent years, wooden laths are used to design gridshells. The most famous example of timber gridshell is Multihalle Mannheim. But the problem in using timber is its weight. As timber has a solid section, the overall weight of the structure increases to a great extent. In a shell structure, huge span can be achieved with minimum thickness. But when using wooden laths the structure might end up looking bulky.

Another natural material, which can perform well as a gridshell, is bamboo. It is a light and a sustainable material. Unlike wood, bamboo has a hollow tubular structure. Unfortunately, it is mostly used in rural areas or for low cost housing. Bamboo has varying material properties. It is not a homogeneous material and to predict its structural strength becomes difficult. To make a free form gridshell out of bamboo, canes are bent and deformed during construction. Not much research has been conducted on the bending behaviour of bamboo. Although most of the bamboo structures involves these curved bamboo elements. The technique of bending bamboo is very well known by local artisans and craftsmen, which is passed from one generation to next. However, it is important to have an analytical study of the same.

Most of the bamboo structures we see today, are temporary structure and are not part of the urban fabric. They are open or semi-enclosed spaces like pavilions and cafe. Bamboo is the least marginally engineered material compared to other materials. Also the combination of bamboo with other standard material is challenging in terms of joinery and fixing. Hence bamboo structure is clad with natural roofing materials like wooden shingles, slate tiles, reed, etc. The choice of cladding material and the type of connection system are the two main reasons that application of bamboo is limited in construction. Of course need for standard codes and bamboo construction regulations, social acceptability are also other reasons for bamboo being under used. Bamboo is often considered as poor man's material. It has failed to live up to the social urban image (Manjunath, 2015). By integrating bamboo with modern construction material and architectural design, its potential can be explored. Hence this thesis deals with integrating this natural material with a high-tech material, thin glass, commonly known as gorilla glass.

Often the phrase "lack of durability" is used for bamboo structures. This issue needs to be further reasoned out to actually understand the problems and challenges. When a matured bamboo is cut for construction, its durability in natural form is around 2 years. But once it is chemically treated, the material can last for 25-50 years (Janssen, 1995) (Schröder & Schröder, 2014). Because of the kind of cladding material selected and joinery developed, the structure falls apart (Figure 1.2b). As mentioned above, cladding materials used are natural materials, which might degrade because of weather conditions. The joints used are simple and developed on site based on the variation of the bamboo material. Most common connections are with using ropes and bolts. The problems with these connections are discussed in detail (Section 5.2). These types of connection systems deteriorates over a period of time. They need to be regularly inspected and replaced. Different alternate joining techniques are investigated in this thesis. The durability of joints in turn increases the life span of bamboo structures. The durability of joints depends on choice of material, detailing of joints and craftsmanship or execution of the joints (Section 1.2c). The connections for this project are developed using reliable materials and detailed considering the advantages and drawbacks of bamboo and thin glass.

The research also deals with understanding the bending behaviour and external influences like pre-bending methods, forces applied and curing methods of bamboo and thin glass. The material structure of bamboo like presence of nodes, tapering along the length can also have an effect on bending. To analyze the potential of bamboo and thin glass structure, a case study is considered. The design of a gridshell roof provides a framework for the research. Through experiments, the maximum curvature of bamboo and the spring back deflection is determined. The experimental results are used to optimize the design of the roof structure and also for detailing. As bamboo is a natural material, tolerances occur to a large extent. Hence this needs to be accounted while detailing the roof structure. This will be a back and forth process where first the geometry of the roof and the desired curved element is determined and analyzed. The curved bamboo members achieved through experimentation method is adapted in the geometry and structurally analyzed.

Thesis Main Goal: To explore the potential and feasibility of bamboo and thin glass structure.

Sub Goal: - Evaluate bending behaviour of both the materials
- Develop a joinery system that can lead to a durable and permanent bamboo structures.

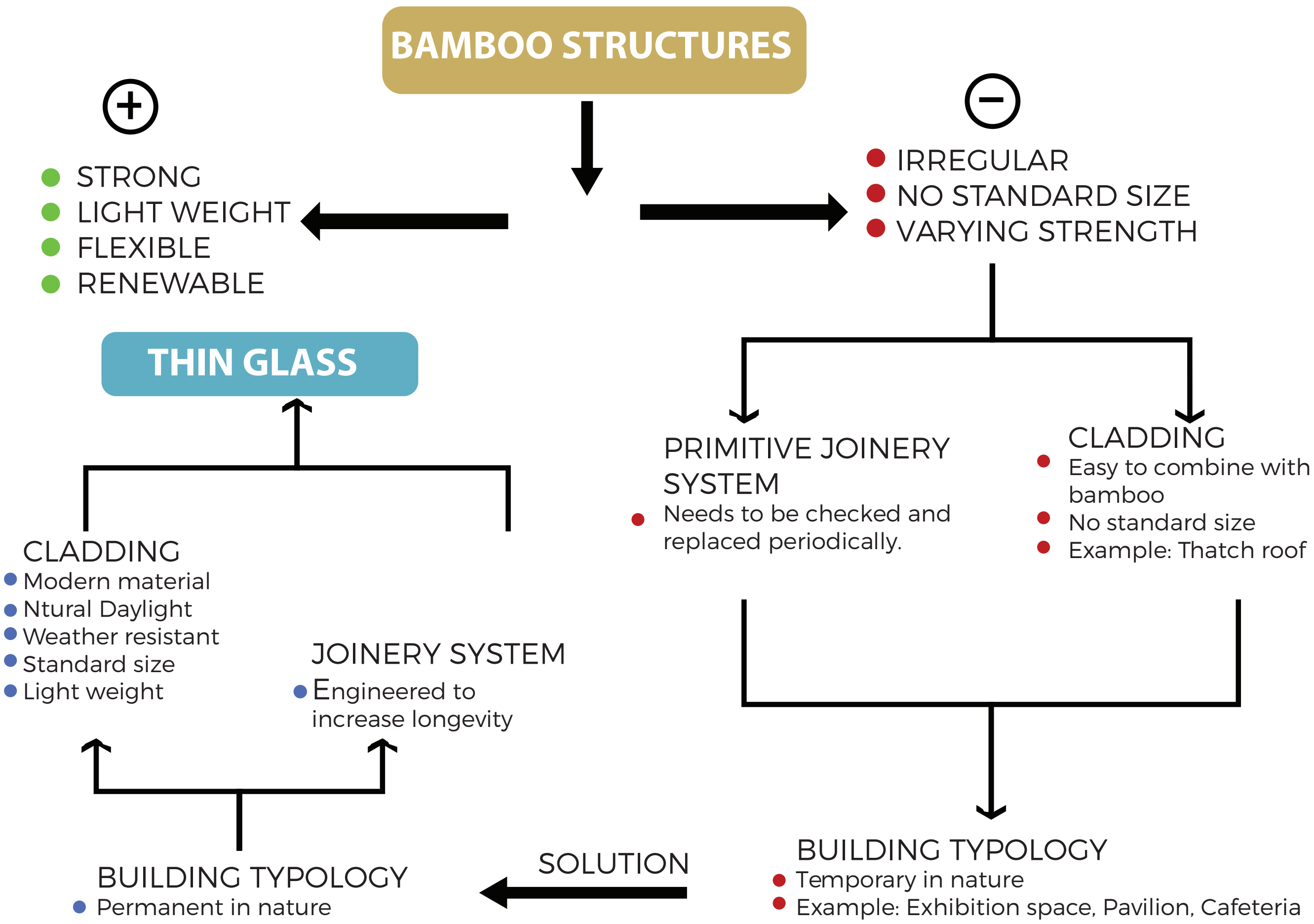


Figure 1.2a: Why bamboo and thin glass?

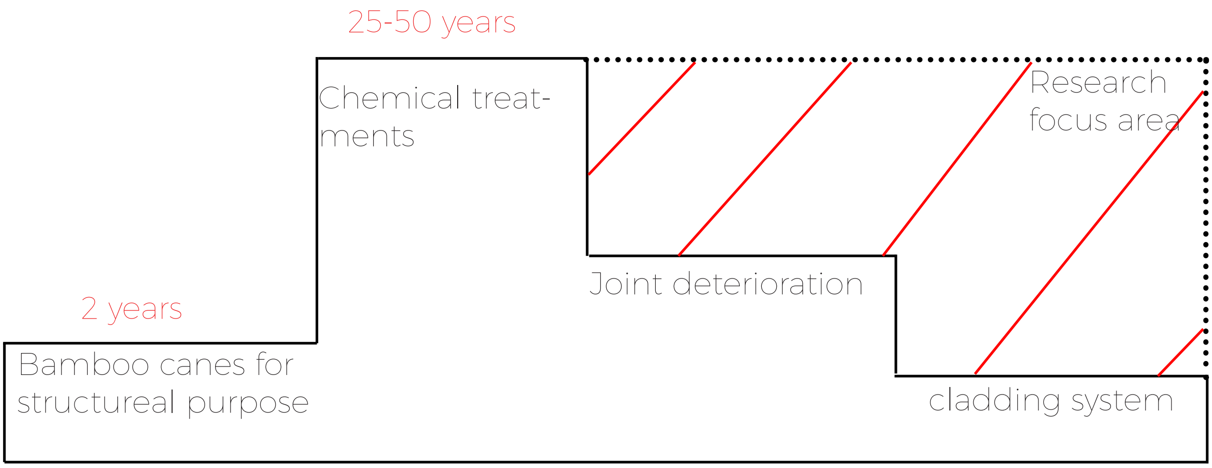


Figure 1.2b: Durability of bamboo structures

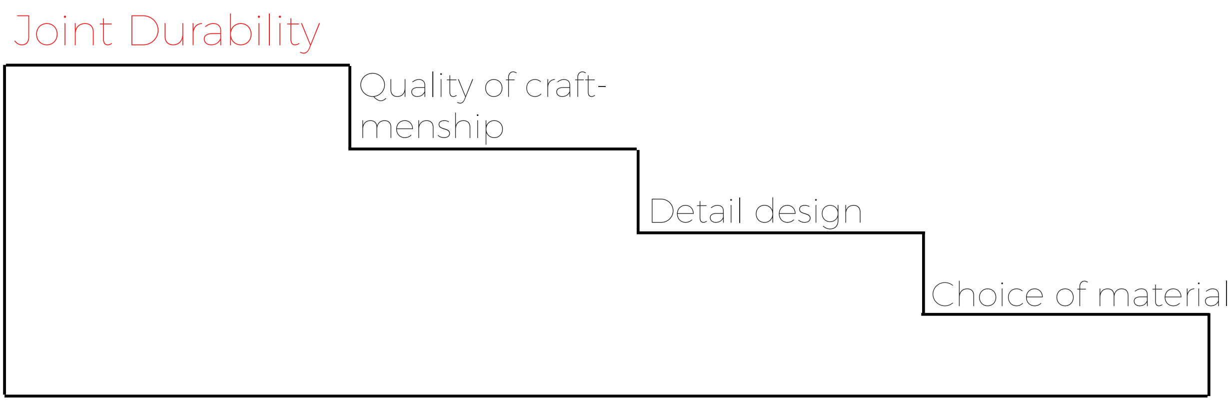


Figure 1.2b: Durability of joints

1.3 RESEARCH QUESTIONS

To achieve these goals, the research is focused on first finding an appropriate form of the gridshell structure out of bamboo. The next part is studying the bending behaviour of bamboo and thin glass. This will be a guideline used to implement free form roof structure. Finally, proposing a joinery system, which has thin glass as cladding material and bamboo as load bearing structure. Hence specific research questions and sub-questions will help to pursue the research.

- What kind of connections and detailing between thin glass and bamboo is required to serve as durable roof structure?

Bamboo is a natural material and is vulnerable when exposed to UV rays and rains. Hence the cladding material will help to protect the skeleton structure and make it long lasting.

- How to deal with tolerances on site in terms of joinery detail?

- Irregularities occur in bamboo in terms of outer wall surface, diameter, length, wall thickness and nodal position. Hence while designing the structure and detailing the joints between bam boo and thin glass these factors are important to study.

- Can one module of glass be bent into different curvature for cladding the roof?

The geometry of the roof is free form and the advantage of using thin glass is its flexibility. Thin glass can be deformed. Hence finding a module of one size, which can be bent in different ways. This helps to save a lot of efforts that goes in customizing each panel, which is usually done for organic cladding.

- What factors should be considered to develop a free form bamboo and thin glass gridshell structure?

- What is the maximum curvature that can be obtained for bamboo?

- The maximum curvature that can be obtained before it yields depends on a lot of factors like type of bending stiffness of the material, bamboo species, section size, thickness, age of the bamboo, curing methods, etc. The radius of curvature that can be obtained by bending should be less than the curvature of the design. If not, the gridshell design needs to be optimized.

- What is the allowable curvature that can be achieved in thin glass?

The flexibility of the glass can be used to adjust with the bamboo grid. But it can flex till a certain limit that is before it reaches its ultimate strength limit and fails. And it can extend till it is stiff enough and the curvature is not inverted because of wind or rain forces acting on it.

- Is it possible to minimize spring back deflection while bending bamboo?

For bending bamboo, force will be applied at different points for a period of time. After this relaxation time the forces will be removed. Bamboo cane springs back to its original position or some other position, which is in equilibrium. The closer the curvature is approximated to the design, the global stiffness of the structure will be less affected. The flow of membrane forces will be according to the shell design. Also the joints can be executed as planned and on site alterations can be avoided.

1.4 METHODOLOGY

Pre-bent bamboo lattices are used for double curved gridshell roof structure. Thin glass, which is flexible and strong at the same time is used as cladding. As mentioned earlier, the goal of the thesis is to study the bending behaviour of bamboo and thin glass. To achieve this, the first step is to find the form and geometry of the roof, which can be used as an example to explore the possibilities. This is done in according to the available material sizes and the maximum curvature that can be obtained for bamboo and thin glass. To study the bending of thin glass, finite element analyis is done, using Ansys workbench software. The maximum curvature and spring back deflection of bamboo are two things considered for this project. This is determined by experimenting with bamboo. Once it is bent, the bamboo should not spring back to its original position. Hence the relaxation time needs to be estimated. This will depend on bending stiffness, type of bamboo species, size and thickness. Based on the experiment results, the structure needs to be optimized. Overall structural strength of the main load bearing roof also needs to be calculated to find the size and number of bamboo stems required, based on its stiffness.

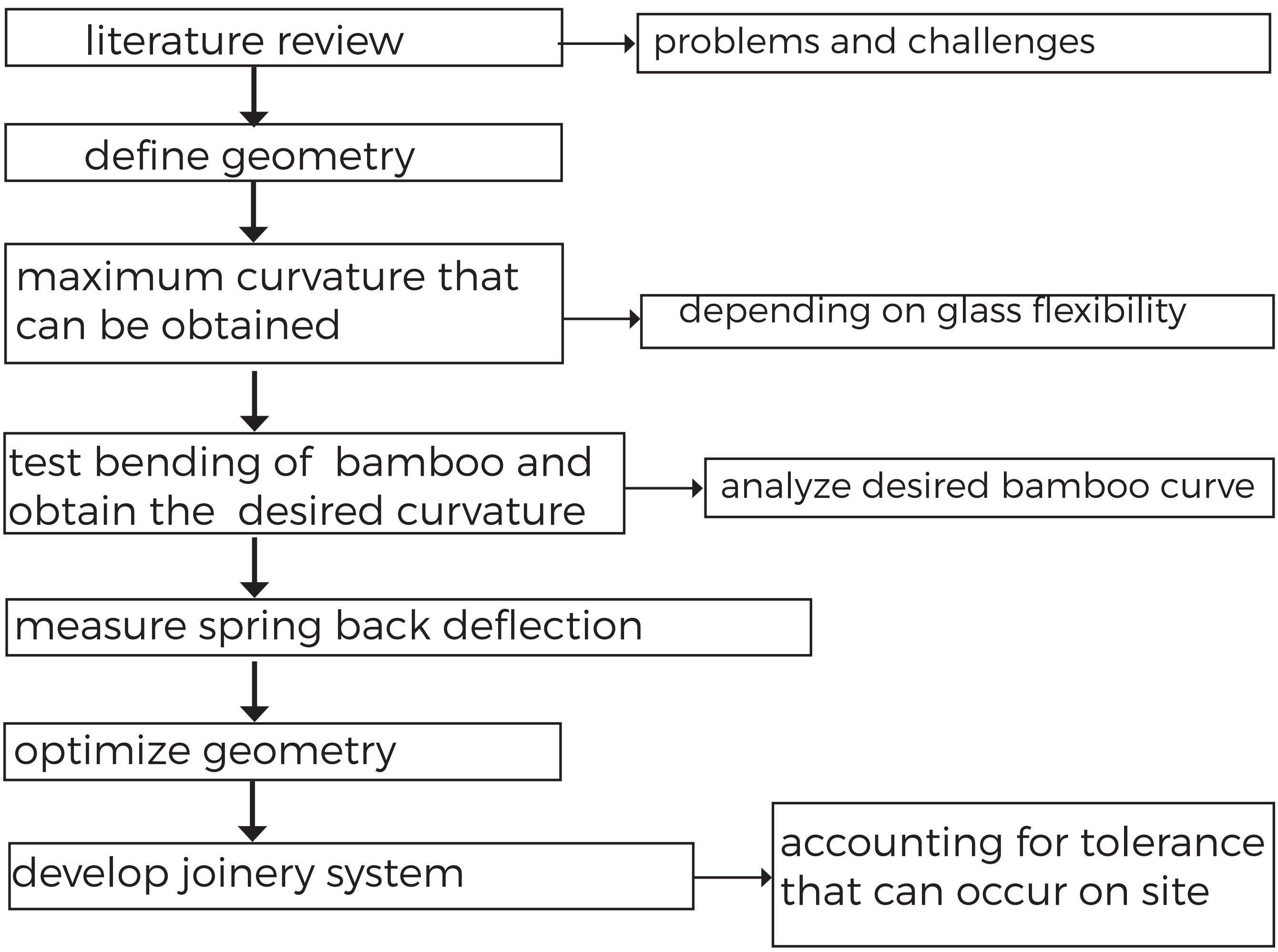


Figure 1.3a: Sequence of research

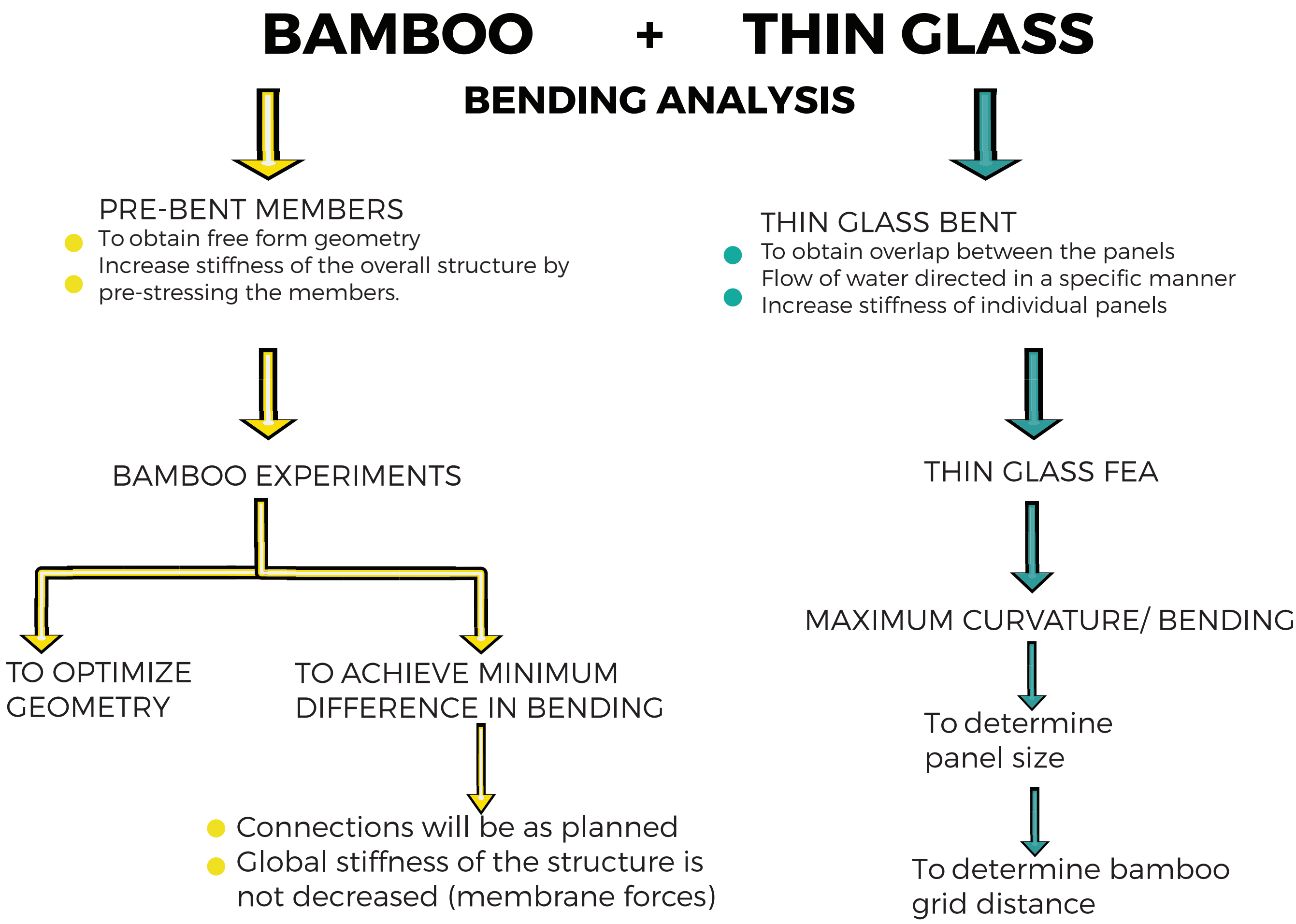


Figure 1.3b: Bending analysis of bamboo and thin glass

BAMBOO

2

There are over 1000 species of bamboo, growing in different parts of the world. It grows in tropical and temperate climates of Asia, Africa and Latin America. Every species has varying mechanical and physical properties. For structural purpose, Gauda angustifolia, Dendrocalamus, Phyllostachys is generally used (Schröder & Schröder, 2010). Gauda is native to South America, Dendrocalamus is found in Asia including India, China and Southeast countries. Phyllostachys, commonly known as Moso is mainly grown in China. Bamboo is composed of vascular bundles, which are supported by fibres and embedded in matrix of parenchyma cells. Hence they can be considered as fiber reinforced composites.

Bamboo is harvested after 3-5 years and kept for drying for few weeks. After this it is ready for construction. The harvesting period and drying duration affects the moisture content of bamboo which in turn is responsible for its strength and other mechanical properties. It should not have very hight moisture content which makes it soft and also should not be very dry which leads to splitting. Because of bamboo's tubular form, it gives a cross section resulting in high moment of inertia. Bamboo is anisotropic in nature. That means the properties differ in all three directions: axial, transverse and radial. It is strongest, when forces act in axial direction. Finally when weight to strength ratio is considered it can compete with steel and is cost effective too.

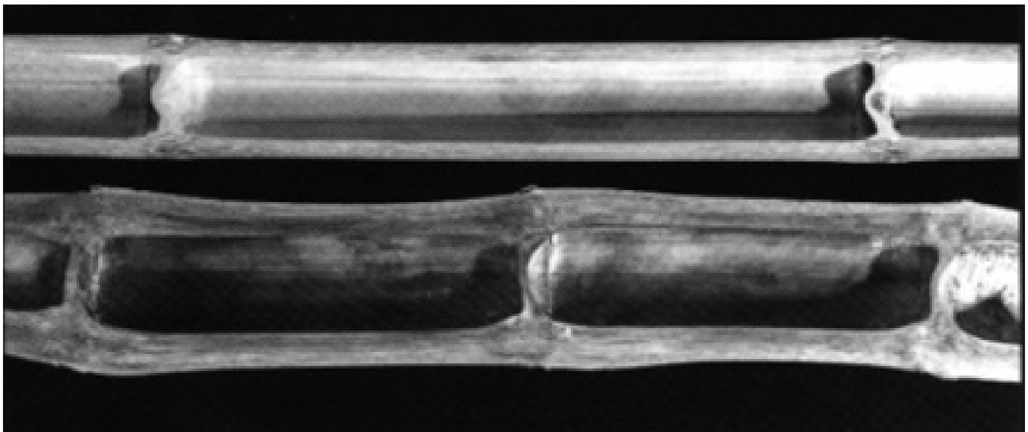


Figure 2.1a: Longitudinal section of bamboo culm. (Lisa,1971)

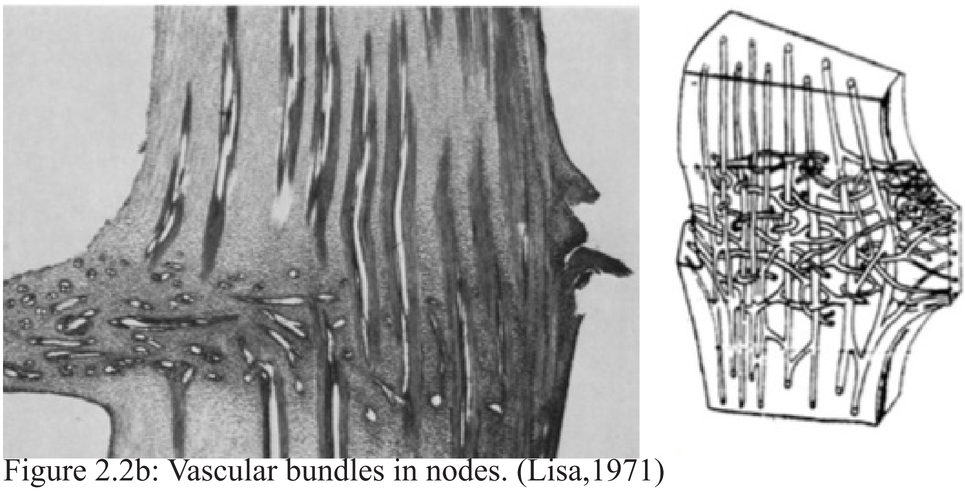


Figure 2.2b: Vascular bundles in nodes. (Lisa,1971)

2.1 BAMBOO MICRO-STRUCTURE

The properties of bamboo differ due to may factors. It depends on type of species, age of the bamboo, post processing treatment. Even the same bamboo shows varying properties. As it starts tapering on the top, the mechanical strength reduces. Also not all parts of the cross section behaves same, the strength starts diminishing from outside to inside. This is because the external fibres are denser than internal fibres. In some species, external fibres shows values close to steel and internal fibres resist only 30% of that (Obermann & Laude, 2004). Hence only the average resistance offered by the entire culm of bamboo should be considered. The length of the internodes increases from bottom to top. It offers best resistance in tension.

Bamboo is divided into nodal and internodal regions. Approximately at every 20cm nodes occur between internodes (figure 2.1a). The fibres are distributed longitudinally in the internodal region and in the nodal regions the vascular bundle fibres are randomly distributed in all directions (figure 2.1b). Usually a joint is seen near the nodes as the fibres are in all directions. It is less prone to splitting compared to internodal regions. The nodes enhance flexural strength of the bamboo and improve transverse resistance to compression and shear. The slenderness ratio of bamboo is (1:150 to 1:250) which is difficult to find in other conventional materials (Meng, Can-gang, Jian-qiao, Shu-cai & Xiong, 2015). In addition it has excellent energy absorption, good elasticity, stable performance and relatively low density.

Bamboo has low shear strength. Hence one has to be careful while designing the joint as perpendicular forces tend to slice the bamboo. Even during bending, cracks developed in bamboo are due to shear stresses and bending stresses depending on the ratio of length and diameter of the bamboo. Due to low modulus of elasticity it is prone to deformations under excess loading.
Nodes had a positive influence on embedment and splitting strength and an overall negative effect on full-culm compression strength and compressive Modulus of Elasticity.

It is also important to note the change in strength of the bamboo with varying moisture content. A lot of research has been done on effects of moisture content on bamboo. Compressive and shear strength decreases for an increase in moisture content (Jiang, Wang, Tian, Liu, & Yu, 2012). Whereas, tensile strength increases with increases in moisture content up to a certain saturation point and then decreases (Gonzalez, Takeuchi & Perozo, 2012). The average moisture content of bamboo suitable for construction is around 55%-65% (Schröder & Schröder, 2010).

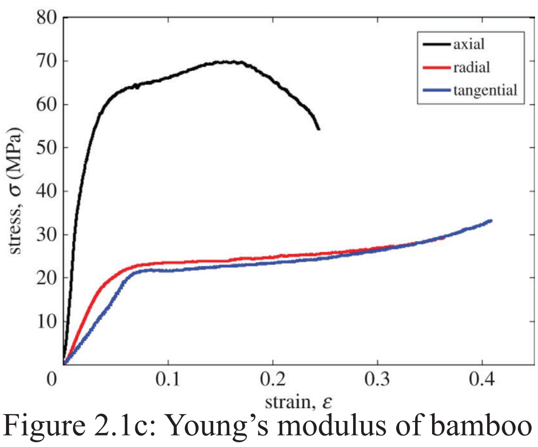


Figure 2.1c: Young's modulus of bamboo in different direction

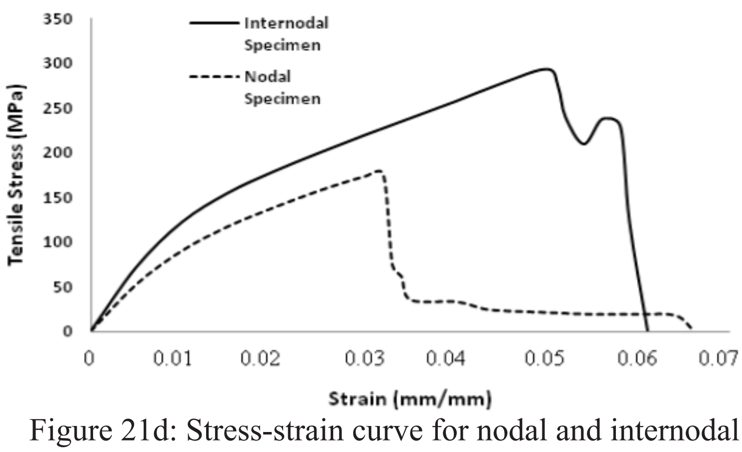


Figure 21d: Stress-strain curve for nodal and internodal specimen in tension.

2.2 PROPERTIES OF BAMBOO

author / year	specifications	compression strength (N/mm²)	tensile strength (N/mm²)	bending strength (N/mm²)	shear strength (N/mm²)	modulus of elasticity (N/mm²)
Martin, Mateus, Hidalgo 1981, Bogotá [MAT81]	age 3-5 years density 0.8g/cm³ moisture ≤ 30 %	62 (max) 49 (ave) 35 (min) 28 (lp)	200 (max) external fibre 70 (max) internal fibre			12000 ($E_{0,max}$) 6000 ($E_{0,05}$)
Garcia, Martinez 1992, Pereira [GAR92]	age 4-5 years density 0.7g/cm³ moisture ≤ 30 % *guadua Macana*	38 (ave) 34 (min) 14 (perm)		30 (ave) 17 (min) 6 (perm)	3.8 (ave) 2.3 (min) 1.1 (perm)	3000 (ave) 2500 ($E_{0,05}$)
Trujillo, Lopez AIS - FOREC 2000, Medellin [LOP00]	age 3-5 years density 0.7g/cm³ moisture ≤ 30 %	65 (max) 44 (ave) 28 (min) 14 (perm)	74 (max) 54 (ave) 35 (min) 26 (perm)	calculated 15 (perm)	8 (max) 6 (ave) 4,3 (min) 1,1 (perm)	12000 ($E_{0,mean}$) 6000 ($E_{0,05}$)
Lindemann FMPA , Stuttgart, 1999 [LIN00]	complete culms, air dry, λ=10 λ=56 λ=86	56 (ave) 39 (ave) 27 (ave)	calculated 95 (ave)	74 (ave)	4,3 (ave) 1,1 (lp)	18000 ($E_{0,mean}$)
Janssen 2000, Eindhoven [JAN00]	density 0.6g/cm³ moisture „air dry“	56 (max) 7,8 (perm)		84 (max) 12 (perm)	12 (max) 1,8 (perm)	20000 ($E_{0,max}$) 10000 ($E_{0,05}$)
average of minimum values by bamboo-space		**~30 (min)**	**~50 (min)**	**~30 (min)**	**~4 (min)**	**~6000 ($E_{0,05}$)**

Table 2.2a: Mechanical properties of Gauda angustifolia kunth, by different authors. Compiled by (Obermann & Laude, 2004).

2.3 FATIGUE IN BAMBOO AND INFLUENCE OF NODES

Bamboo is a natural fibre-reinforced composite material. When deformed it undergoes slight plastic deformation. As it reaches its ultimate limit strength, brittle fracture occurs. This deformation is different from plastic deformation occurring in metallic materials. Nodes have significant effect on energy absorption, subjected to force axially.

In the internodes, the fibres show gradient distribution. The density of fibres decreases gradually from outside to inside. Bamboo when fractured, splits. This is because, there are large number of voids between the fibre arrangement. Under axial loading, the nodes becomes swollen and retain the nodal diaphragm and protects the bamboo from splitting (Meng, Can-gang, Jian-qiao, Shu-cai & Xiong, 2015). This shows that nodes increases anti-split property and tensile strength of bamboo. The nodes are not easily damaged and thus absorbs more energy. The diaphragm act as stiffeners and gives stability to the structure. However, if the load exceeds, longitudinal cracks propagate in the internode.

Under continuous loading, bamboo components commonly experience bending. This causes ovalisation of cross section and stresses arise which leads to fatigue. But there are different stages of deformations before final failure occurs. The following experiment was carried out by Keogh et al, to understand the fatigue behaviour of bamboo.

The cross section is divided into four points: N, S, W ane E. A bamboo specimen was subjected to compressive loading transversely. It was understood that usually in stage1, initial cracking occurs at one of the two locations, W or E . This is because of slight difference in the geometry through thickness. The weaker side will fail first. In stage 1 stresses have already been generated on the opposite site (17.6%). A significant number of cycles elapsed till the second crack appeared. The onset of stage 2 increases stresses at point N ans S (31%). And in the final Stage C, once cracks are propagated at points N and S will lead to a total collapse. Even though, the material on the outside of the culm is denser and hard compared to the material inside, it appears to have a lower toughness. Hence fatigue cracks propagate easily from small defects at W and E (Keogh, O'Hanlon, O'Reilly & Taylor, 2015).

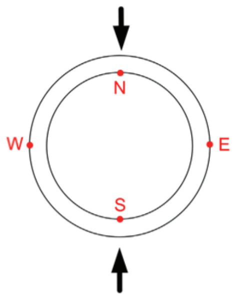


Figure 2.3b: Transverse compression gives rise to high tensile stresses at four locations around the circumference: the stress on the inside surface at points N and S is approximately twice as high as the stress on the outside at points W and E.

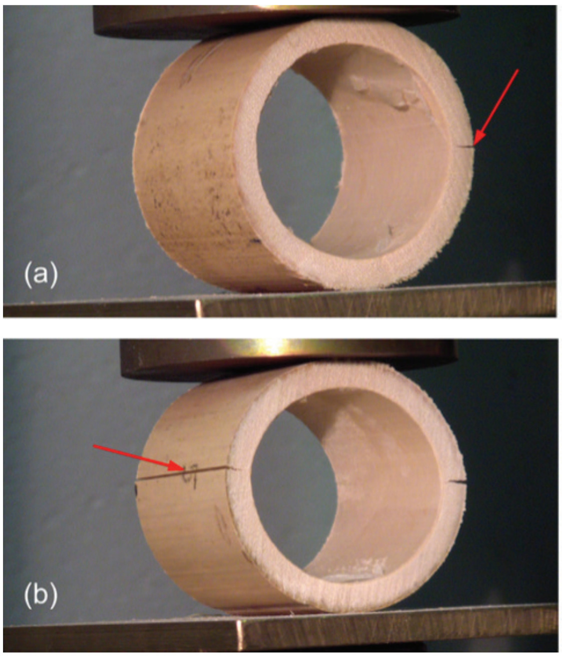


Figure 2.3a: Crack formation at Stage A and Stage B, for diametrical compression tests.

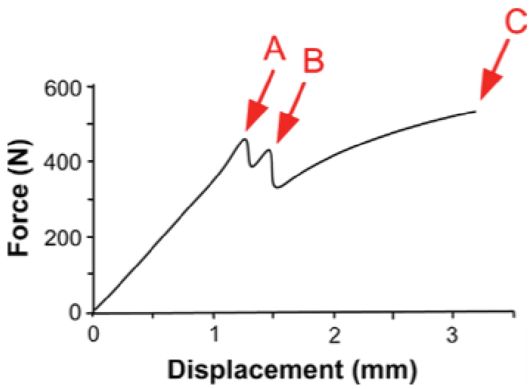


Figure 2.3c: Force-dispacement curve at different stages

GLASS

3

3.1 GLASS COMPOSITION

Based on the application of glass, the composition of glass changes. Different formulas and glass production technique change its mechanical, electrical, chemical, optical and thermal properties. A typical glass contains formers, fluxes and stabilizers (Cmog.org, n.d.).

- Formers are the largest percentage of glass composition. In most cases silica (silicon oxide) in the form of sand is used.
- Fluxes like soda (sodium carbonate) or potash (potassium carbonate) lower the temperature at which the formers melt.
- Stabilizers like calcium carbonate, makes the glass strong and water resistant.

For the construction industry, soda lime silicate glass is used, which has the following composition:

- Silica in the form of sand (70-72%)
- Soda as flux in the form of carbonates and sulphates (14%)
- Lime as stabilizer in the form of limestone (10%)
- Oxides such as alumina and magnesia to improve physical properties of glass and resistance to atmospheric pollutants.
- For tinted glass, metal oxides are added.

A new generation of glass is under development for building application.

3.2 THIN GLASS

Glass technology has evolved and efforts are being made to produce lightweight flexible glass. One of the successful product in this technology is thin glass which is chemically strengthened and 5 times stronger than thermally tempered glass (S.AGC, n.d.). The thickness of this glass is as low as 0.5mm. This opens doors for architects and designers to use a flexible cladding material without compromising on safety and aesthetics. This next generation glass offers superior clarity without any green tint, as there is no iron or soda lime. It has outstanding scratch and weather resistance. The flexibility is like a plastic sheet but maintaining the durability of glass. It is widely used in electronic gadgets like smart phone, tablet, LCD screen.

A conventional glass breaks because of flaws due to impurities or processing. When under tension cracks propagate where there are flaws. But thin glass takes in charged particles (ions), which increases the surface compression. The sodium ions (Na^+) present on the surface of the glass is replaced by potassium ions (K^+) when dipped in a solution of potassium nitrate. The K^+ ions have a larger diameter than Na^+ ions. This exerts compressive stress on the glass as larger diameter ions occupy the same space as smaller ions with smaller diameter (Neg.co.jp, 2000). The squeezing action is compressive stress on glass surface and when force is applied to the glass which will crack it, the compressive stress helps to cancel it out and prevent from cracking (figure 3.1e).

Leoflex glass is one of the companies, which is developing thin glass for architectural purposes.
Thickness: From 0.5mm to 2.0mm
Size: 48” x 29”. (1.2x0.75m)

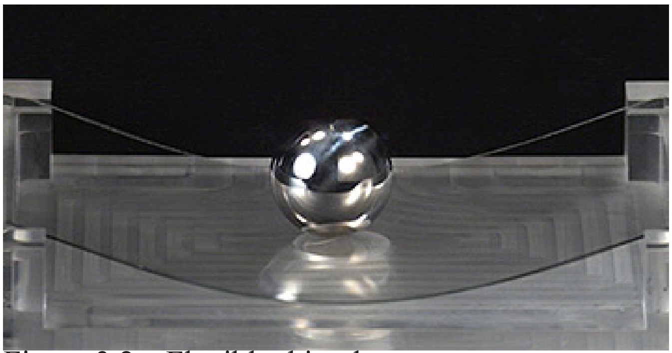


Figure 3.2a: Flexible thin glass.

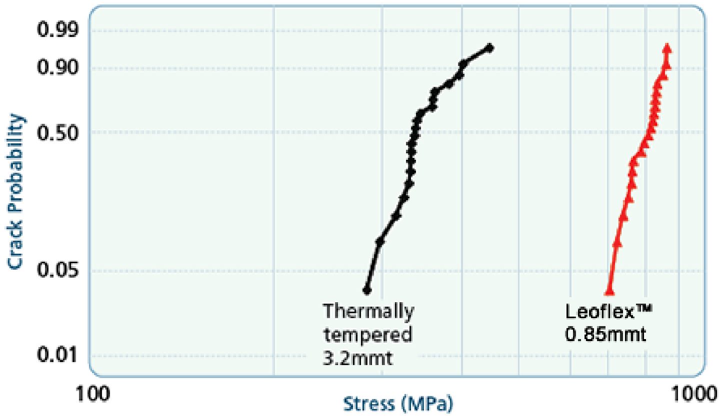


Figure 3.2b: Comparing strength of thermally tempered glass and thin glass.

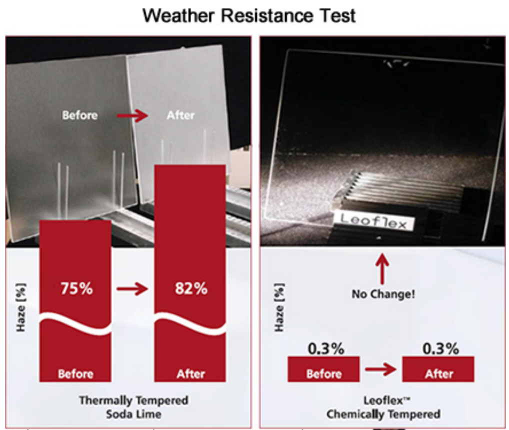


Figure 3.2b: Comparing resistance to weather of thermally tempered glass and thin glass.

	Property	Measurement	Leoflex™	Soda Lime
Mechanical	Density	g/cm^3	2.48	2.50
	Young's Modulus	GPa	74	73
	Shear Modulus	GPa	30	30
	Poisson's Ration		0.23	0.21
	Vickers Hardness	Before CT	595	533
	Vickers Hardness	After CT	673	580
Thermal	CTE	[10^{-7}](50~200°C)	98	85
	Tg	°C	604	550
	Softening Point	°C	831	733
	Annealing Point	°C	606	554
	Strain Point	°C	556	511
Optical	Refraction Index	Nd	1.51	1.52
	Photoelastic Constant	nm/cm Mpa	28.3	25.6
Electrical	Volume Resistivity	log (Ω·cm)	8.4	8.5

Figure 3.2d: Properties of Leoflex thin glass

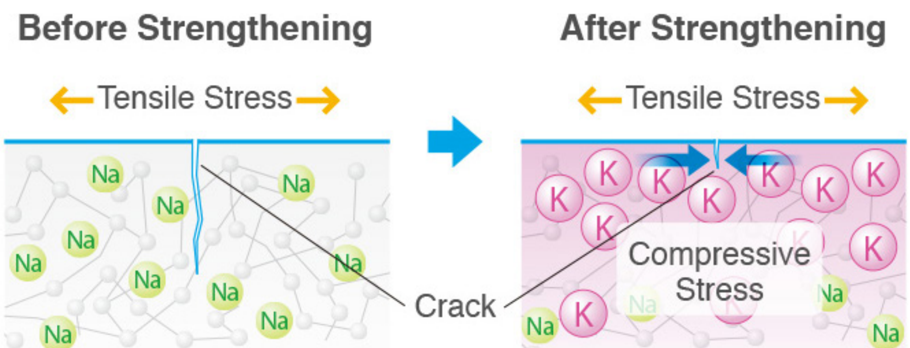


Figure 3.2e: Glass strengthening, ion exchange process in thin glass.

3.3 GLASS PROCESSING METHODS

FLOAT PROCESS

In modern glass processing method, float process is most conventional technique to manufacture glass sheets. The raw materials for this process are discussed earlier (section 3.1). Molten glass floats over a molten tin bed and as it moves through the bath, it is cooled. At a certain viscosity level, the glass is spread out by applying pressure to a desired thickness. It is then tempered to prevent the formation of stresses. Fully tempered glass is cooled as fast as possible, whereas, heat strengthened glass is cooled more slowly. For structural glass, heat strengthened is preferred because it has less crack developments or fragments when it breaks.

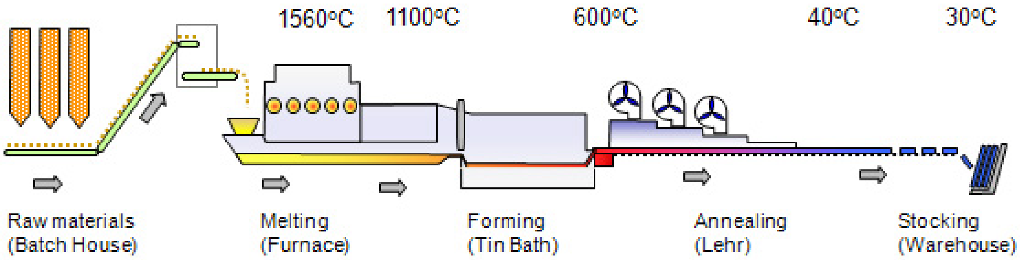


Figure 3.3a: Float process.

THIN GLASS_FUSION OVERFLOW PROCESS

This method was introduced by famous glass making company Corning in the 1960s. Molten glass is poured into a trough, which is tapering downwards. The trough overfills and excess molten glass flows over both the sides of the pipe in two streams. The streams combine and form a single sheet. The glass that touched the surface of the trough is trapped on the inside of the sheet. Edge rollers draw down the sheet. The edges of the sheet are cut away, leaving behind a pristine surface sheet.

Because of the flow gravity, surface tension is created. This leads to substantial flatness. Unlike the float process, the sides of the glass have absolutely no impurities. In float process, the sides touch the tin bath and may need to be grind or polished post process. But in fusion overflow process, both sides of the glass are untouched.

Figure 3.3b: Fusion overflow process.

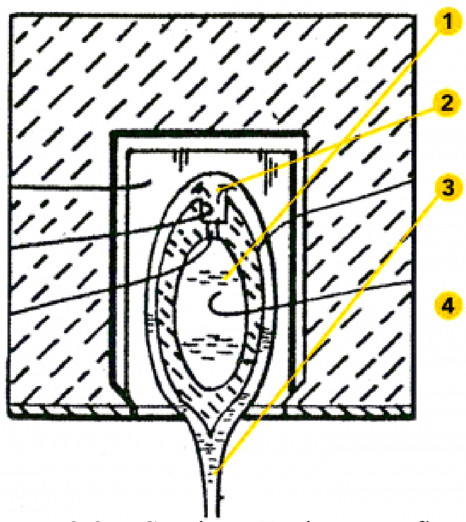


Figure 3.3c: Section. Fusion overflow process.

THIN GLASS_DOWN-DRAW PROCESS

This technique of producing thin glass has been developed at Schott AG (Mainz, Germany). Molten glass passes through a nozzle and roller system, forming ultrathin glass. Naturally fire polished sheets are produced, eliminating post processes like grinding and polishing. The thickness of the glass range from 1.1mm to 20 μm. The defect level of the surface is as low as ±5 μm. Low thermal expansion (3.25 ppm/K) and high temperature stability (>600ºC) is achieved (Overton, 2012). The process is flexible in terms of changing the raw materials as per application. Earlier glass sheet measured 30x40cm, but now a wide range of sizes are possible up to 1900x2200mm.

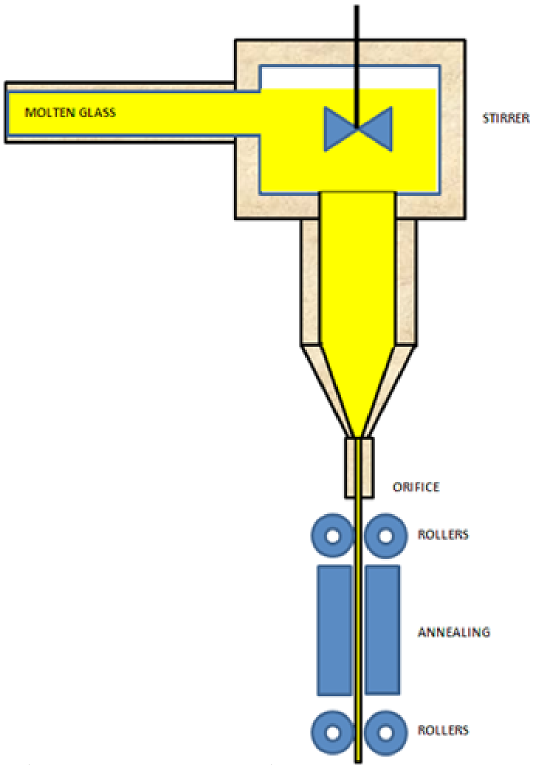


Figure 3.3c: Down-draw process.

3.4 THIN GLASS PRECEDENT

1. Brazil FIFA World Cup 2017, Players Bench Roof:

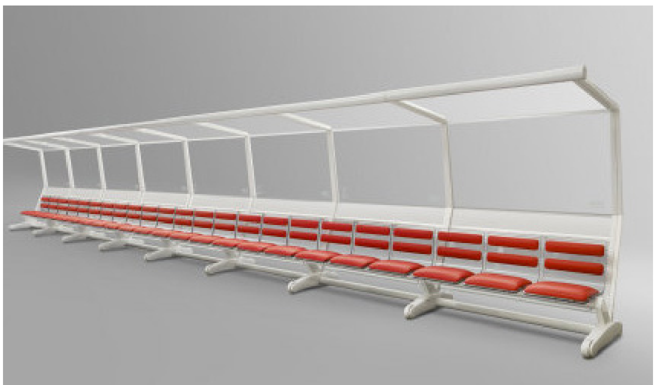
The glass roof, made from chemically strengthened thin glass, provides unparalleled visibility, durability and damage resistance. This technology, originally developed to protect small electronic devices such as smartphones and tablets, can be applied to large fixtures, paving the way for greater potential for chemically strengthened glass to be explored by architects and designers.

The player benches composed entirely of AGC-made materials such as fluoropolymer-coated frames made with fiber reinforced plastic. One of the key attributes of the glass roof for player benches for the 2014 FIFA World Cup Brazil™ is clear visibility. The rear portion of the bench is applied with anti-reflective coating, making its reflective properties 13 times lower than conventional glass to ensure the best-possible visual experience for football fans. Protection for players and staff on the bench is provided by a double layer of chemically strengthened Dragontrail™ X. Dragontrail X is characterized by low center tension and high compression stress. The technology, first showcased at CES 2014, makes glass exceedingly durable against external shock. It is up to eight times stronger than soda lime glass. The new glass roof is also highly resistant to scratching, as well as deformation and discoloration, promising years-long product life even in outdoor environments characterized by fluctuating temperature and humidity.

Bench Statistics (Players bench)
Dimensions
Length: 11.5 meters
Height: 1.9 meters
Depth: 1.0 meter
Glass thickness (backpanel): Approximately 3.5 millimeters
Number of seats: 23

- Achieves high level of surface strength
- Anti-reflection coating
- Reduces reflection rate to 1/13 that of conventional glass.

Dragontail glass:
Size 3mx3m
The lower edge of this flexible glass, which is just 0.56 mm thick, can be curved to a radius of less than 3.2 centimeters, allowing the glass to stand on its own. At a wind speed of eight meters per second the edge of the glass can move more than 5cm.



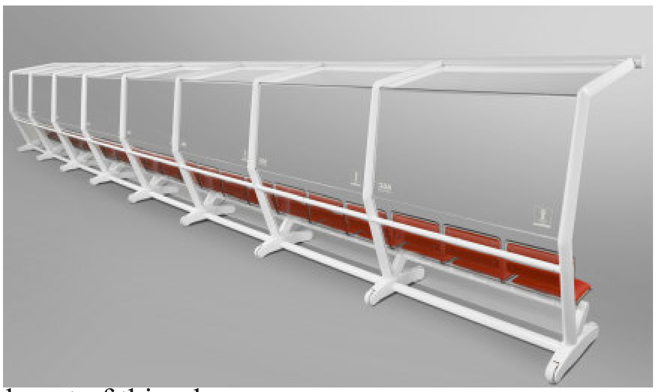


Figure 3.4a: FIFA world cup 2014, players bench made out of thin glass.

2. Retractable Canopy

A deployable canopy out of thin glass was developed by Xiang Wang at TU Darmstadt.This folding roof was exhibited at the glasstec 2014. The thin glass is of two layers laminated together with two layers of PVB. Glass is cold bended to form conical arch. The lamination retains the cold bended glass in the required curvature. The panels are fixed using mechanical fixtures which are bonded to the glass.

Span: 3m

Length: 3.4m (open).

0.65m (close)

Glass Layer: 0.7mm gorilla glass - 0.38mm PVB interlayer - 0.7mm gorilla glass.

Panel size: 750mm x 1250mm

Figure 3.4b: Folded thin glass roof at glasstec 2014.

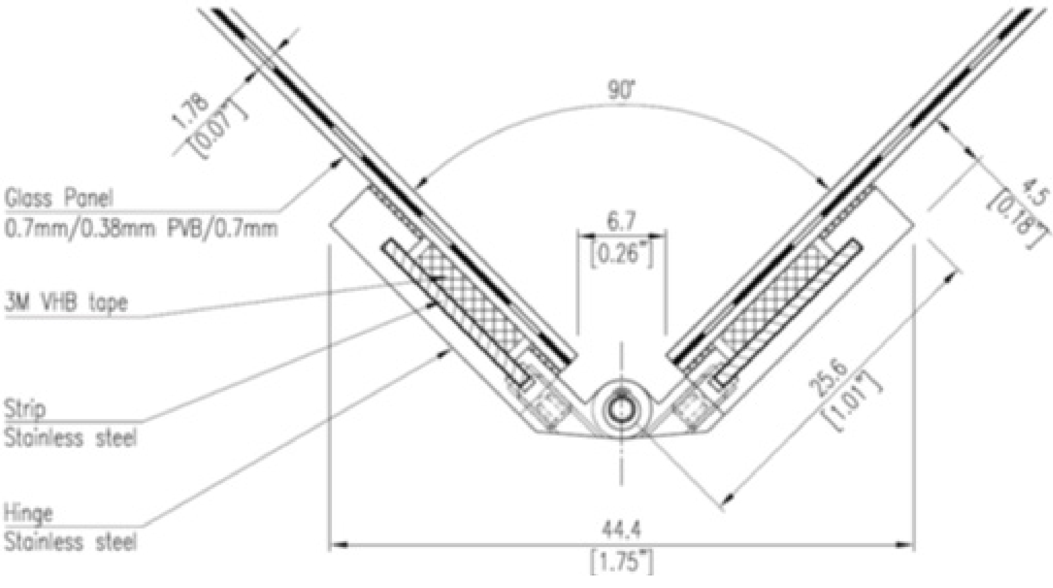


Figure 3.4c: Folded thin glass roof connection detail.

BAMBOO - PRECEDENT

4

Overview of some modern gridshells made up of bamboo is presented below. In recent years architects have been trying to design structures with organic forms. To implement such forms, material plays an important part, where freedom to bend and twist the material is required. Different construction techniques with exploration of new materials have advanced over the years. Right from using wooden form work for in situ concrete shells to using inflatable membrane formwork for same kind of concrete shells. This method was used for constructing Bini-shell in by (figure 4.0.a). Thus advanced methods proving to be economical and less labour intensive. Similarly, gridshells made of connected members is built with highly sophisticated construction techniques or produced using old handcrafted methods in developing countries. Some of these old techniques prove to be efficient even today. For wooden gridshells, curved laths can be used for construction. The laths are either pre bent or bent after assembling the whole structure. When using the later technique, a 2-dimensional mesh transforms into a 3-dimensional space. This kind of assembly and structure is discussed in section 7.6. Different materials permit different kind of construction method. So if curved bamboo is used for developing a gridshell, this method of bending while assembling cannot be used as it is prone to splitting in the direction of fibres. Bamboo needs to be processed before bending it, as discussed in section 6.1. Further analysis on shell structures is done in section 7.

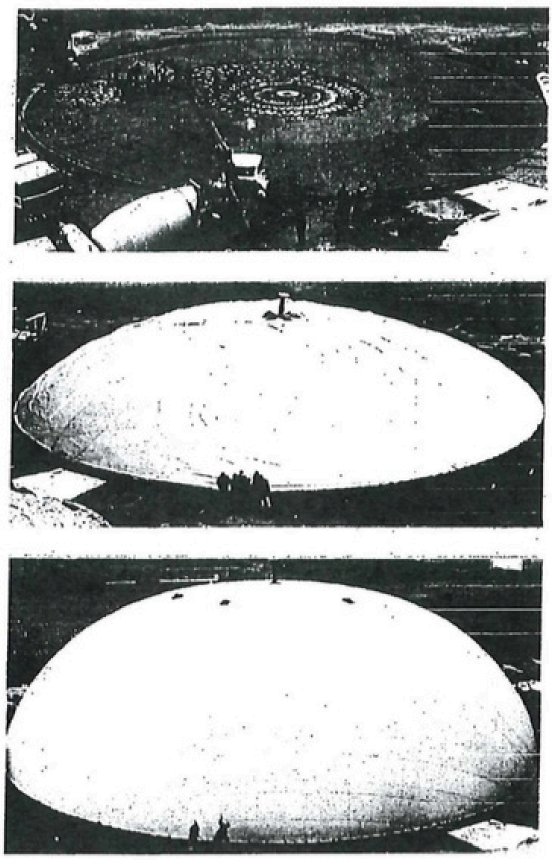


Figure 4.0a: Construction process of Bini-shell

The examples studied below, include structures made with straight and curved bamboo elements. Most of the structures are built in Asia, where the material is available abundantly. There is a Bamboo pavilion which is built in Germany. Thus increasing the popularity of the material in western world. Even though bamboo needs to be exported to these regions, because of fast production of bamboo and light weight, energy used to export this material is less compared to other mconstruction materials.

The structures selected for study having different type of geometries like dome, vault and double curved free form structures. These examples have been an inspiration to develop a form for further research on bamboo and thin glass structure. In these examples, the form of the bamboo roof is developed not only for artistic endeavor, but is climate responsive. It is interesting to study the way this lightweight gridshell structure transfers the load coherently.

Few of the precedents are analyzed for its structural stability. Comparison is done of straight and curved elements using the same example. For instance if a structure is made up of curved element, the same geometry is replicated using straight elements. A part of basic geometry was modeled using software Rhinoceros and then exported to Ansys workbench. In Ansys, using FEM vertical deflections were compared. The geometry was not assigned bamboo as the material but used default structural steel as the aim was to compare the geometric form and not analyze the overall structure and failure behaviour. This comparison was done to study the advantages of curved elements over straight. As constructing with curved elements would require processing and pre-bending each element and turns out to be more time consuming. Hence the question was whether curved elements have any structural benefits. Based on FEM results, it was found that the deflections were less when curved elements were used. Pre-stressed elements can carry larger loads compared to straight elements. Although bending stresses are induced during pre-bending, but during relaxation period most of the stresses are reduced.

Because of the curved, arched elements, it is possible to have large spans without or few supports in between. This is because the load is carried mainly in compression instead of bending action. The curvature of the bent elements is the most important factor since it determines moment and level of strains that will develop during pre-bending process (Miura and Pellegrino).

After analyzing the precedents given below, the decision was taken to consider a gridshell of pre-bent bamboo members for the case study (Section 10).

4.1 ECOLOGICAL CENTER - 24 ARCHITECTS

The children's activity and learning center is part of six senses' Soneva Kiri resort on the island of Koh Koodin, Thailand. The structure is made of locally sourced, labored bamboo and the design is environmental friendly. The structure is mounted on a rocky slope, which spans out towards the bay. The most interesting feature is the 8m cantilevers on both sides of the structure. This exemplifies the strength of bamboo. The canopy is cantilevered in order to provide adequate shading from the sun and protection from the rain. The interior is covered with laminated wood flooring. To separate the functions, many domes are constructed out of wood, which is weaved like a large scale wicker basket.

The structure spans around 26m in both the directions. The framework of this canopy is made entirely from bamboo, which is tied and bolted together. Bamboo reeds of all sizes are used for this construction. Larger bamboo canes are used for the anchoring columns. These columns are fixed to concrete pylons by reinforcing bamboo with steel bars. The roof is made of small size bamboo to maintain lightweight of the structure. The grid of the roof is made of two bamboo poles attached together. This gives the structure a safety factor and prevents it from complete failure even if one bamboo breaks or fractures. The roof covering is also made from split and flattened bamboo tiles.

The key to strength of the structure is because of the double curved surface, which gives extra stiffness. This double curvature locks the shape giving extra rigidity to structure. Even buckling strength is more compared to a single curved structure. The roof is hyperbolic paraboloid, simultaneously curved in opposite directions as a result of which it is resistant to buckling. Hence, its helps to optimize the amount of material used and proved to be economical. In this case the bamboo canes used for the framework are curved.

The design compliments the humid tropical environment climatically. Inside the structure, the floors are setback, allowing natural airflow and daylight. Thus limiting energy consumption cost. Also the cantilever roof protects from heavy rains and provides shade.


Figure 4.1a


Figure 4.1b


Figure 4.1c


Figure 4.1d

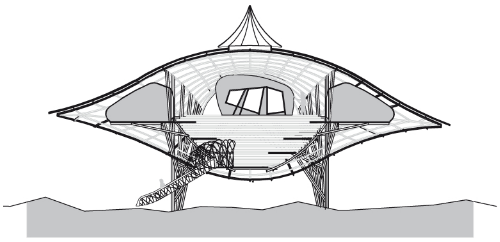


Figure 4.1e: Cross section

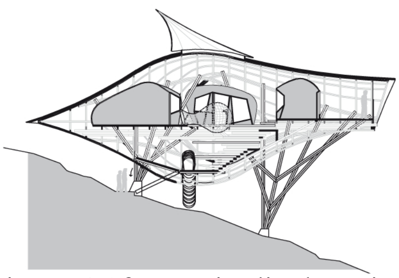


Figure 4.1f: Longitudinal section

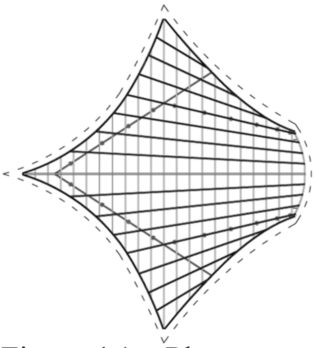


Figure 4.1g: Plan

Structural analysis is done, to compare the roof structure which is a double curved surface made of curved bamboo framework and hyperbolic paraboloid surface made of straight bamboo framework. It is observed that deflection of the structure made from curved framework is less than deflection occurred in straight grid framework

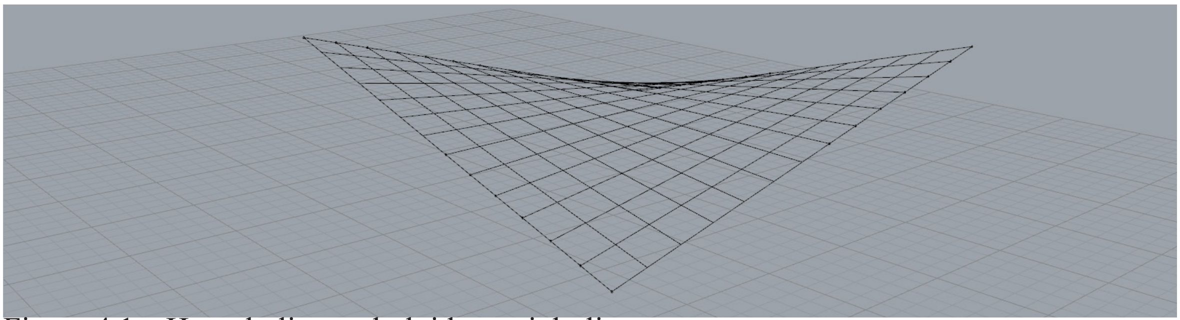


Figure 4.1e: Hyperbolic paraboloid - straight line generator.

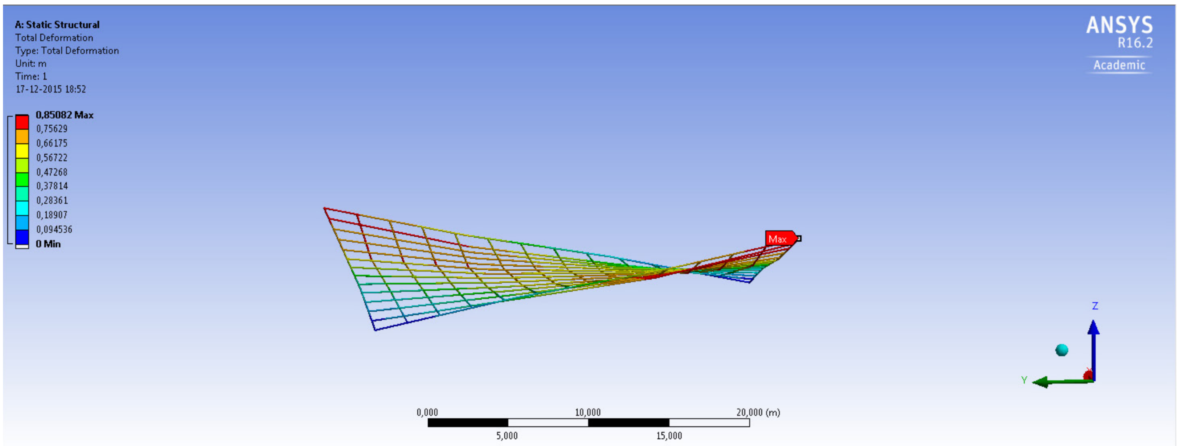


Figure 4.1f: Hyperbolic paraboloid - straight line generator. Deflection = 0.85m

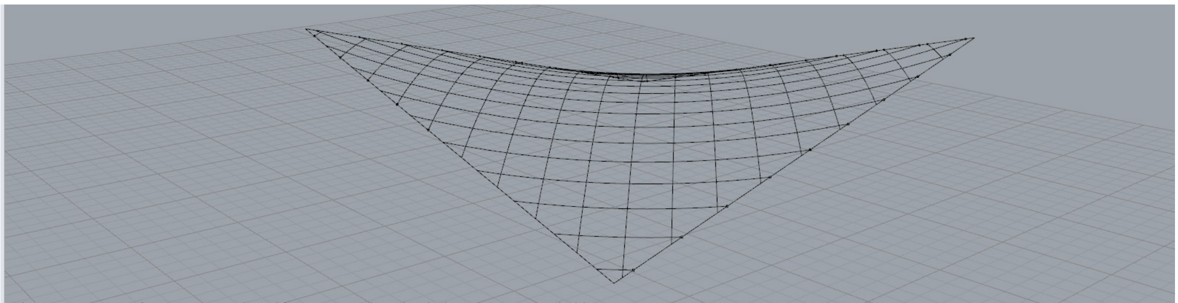


Figure 4.1f: Hyperbolic paraboloid - curved line generator.

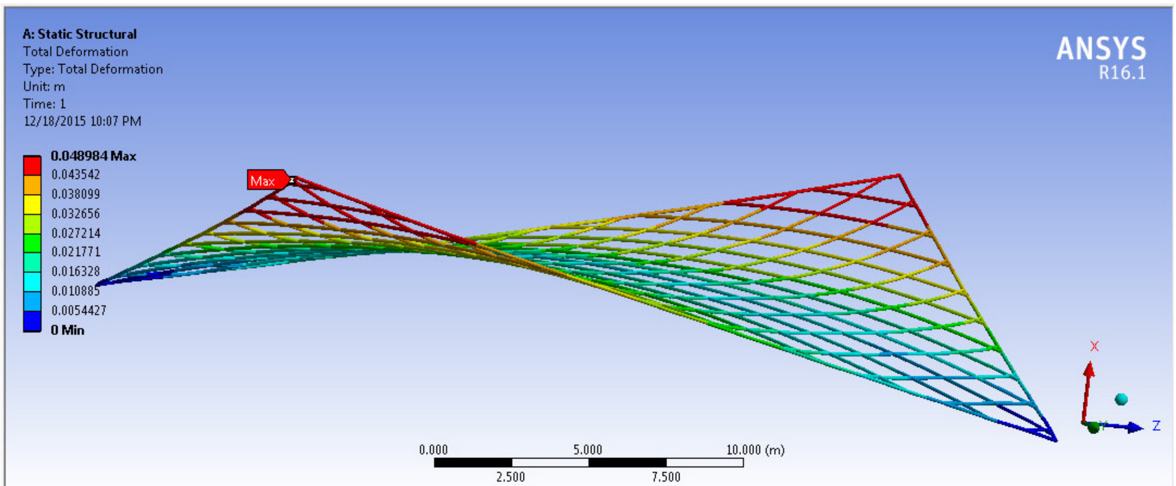


Figure 4.1f: Hyperbolic paraboloid - curved line generator. Deflection = 0.04m

4.2 ZARI PAVILION - SIMON VELEZ

This pavilion is built in 2000 for Hanover expo. It is designed by Simon Velez, famous for his bamboo works. It is a circular polygonal roof supported by two concentric courses of 20 pillars. The circular form is segmented by 10-sided polygon which tapers to form the roof of the structure. It is a two storied structure. Alternate vertical supports arise from the first floor. Hence the pillars are of two sizes in length: 8m and 14m. The first floor comprises of galleries which is 500m² and the ground floor is 1650m², together a total area of 2150m².

The wide overhanging roof is a special feature of the architect's design and is seen in many of his other works. The reason behind the overhang roof is to protect the structure from rains. It is overhanging up to 7m around the entire perimeter of the structure. The structural framework consists of two concentric pillars supporting the roof which is cantilevering on both sides. This system is repeated radially to form the pavilion. The bamboo framework of the roof tapers to form a ridge ring. The roof is made up of ten beams concentric to the ridge beam. In between these beams there are secondary beams but they don't transfer the loads directly on the pillars. Main beams support the secondary beams.

The span of the roof is 40m with a ridge height of 14.5m and valley height of 7m. The framework is clad with cement tiles. There are total 40 main roof girders radially arranged at angle of 9°. Adjoining members support alternate girders, using diagonal rods and rings. These girders are bundles made of 8 bamboo canes. The canes are connected with using steel clamps except at ends where it meets the pillars, bamboo is additionally filled with mortar. Vertical supports are bundled with 6 and 4 bamboo canes outside and inside respectively. Only 2 canes are used for transferring loads to the foundation. The rest are used to increase flexural rigidity of the system. The bracings used to support the floor and roof to some extent is made using lower part of the bamboo as it has more strength.

It is interesting to see that all elements used in this structure are made of straight bamboo canes. Hence this saves a lot of time and material cost for shuttering compared to canes, which are curved for structural purpose.


Figure 4.2a


Figure 4.2b


Figure 4.2c

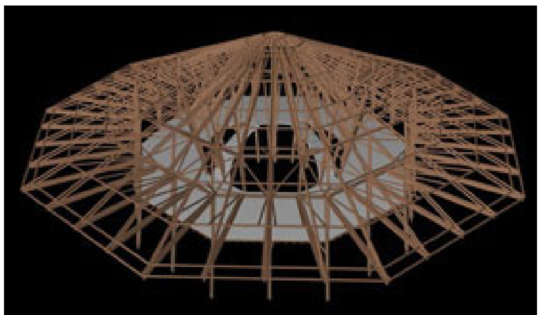


Figure 4.2d

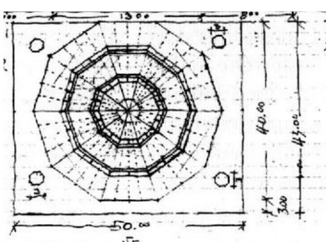


Figure 4.2g: Plan

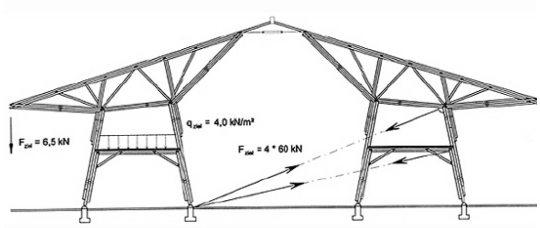


Figure 4.2f: Section

3.3 CURVED BAMBOO DOMES- VO TRONG NG-HEIA

The trio architects Vo Trong Ngheia, have worked extensively on bamboo dome roofs. Their principle element, curved bamboo canes are used in all structures. They believe that important character of bamboo is that it is bendable. This gives flexibility to use it as a structure with unique shapes. In most of their structures, bamboo canes are joined together in a low-tech manner, using rattan and bamboo nails. Steel bolts are avoided to prevent shear longitudinal splitting, which eventually leads to buckling in columns. Even the processing of bamboo to eliminate pests is done in a traditional way. It is first soaked in mud and smoke treated to increase its durability.

The dome bamboo roof structure studied in detail is community center in Vietnam. It is located on Saigon river peninsula in Ho Chi Minh city. This comprises of 8 pavilions of different sizes, providing series of large and small multi-use spaces for the community. The dome roof is covered with thatched roof. These domes are spread across the park having two large dome modules with 12.5m in height and approximately 25m span. The pavilions look like giant mushroom shells. The framework is inspired by the traditional bamboo weaving basket technique.

To support the roof, bamboo canes of various lengths are bundled together which acts as pillars. These pillars then continue up and are connected to the rings of the roof. The larger pavilions were constructed on site and the smaller pavilions were prefabricated as 12 parts and assembled on site. In the two large domes, the bamboo framework is bifurcated creating two layers. The outer layer of framework supports the thatch roof, which has overhangs to protect from harsh sunlight and heavy rainfalls.

The domes are well ventilated with openings on the top which also provide natural lighting, during the day.


Figure 4.3a


Figure 4.3b

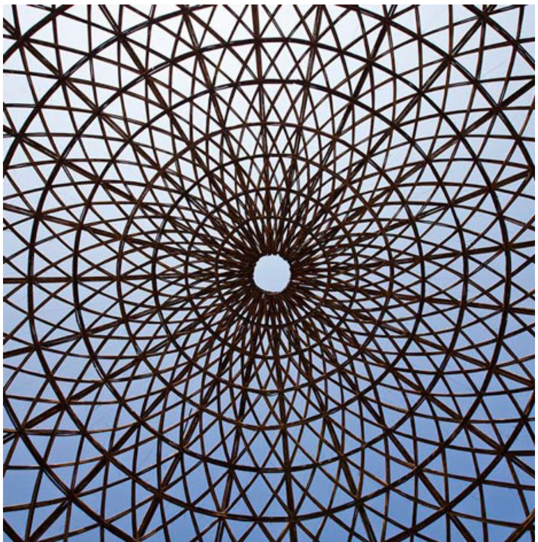


Figure 4.3c


Figure 4.3d: Sectional elevation

4.4 GEODESIC DOMES

Geodesic domes are partial spherical shell or lattice shell structures. The dome is made up of triangular elements, which are divided and sub-divided to form a surface structure close to a spherical surface. The more the number of divisions smoother the surface and hence the stress distribution is even as in case of a sphere.

A geodesic dome is usually constructed using an icosahedron. An equilateral triangle can be subdivided into 4, 9, 16 or any perfect square. The vertices of the original icosahedron will lie on the surface of the sphere, while the new vertices introduced to subdivide the triangle are pushed outside the surface to form the sphere. The number of subdivisions of the triangle are called frequencies, the original triangle being 1V and as it divides the frequency rages from 2V, 3V, 4V and so on (figure 4.4a).

Many experiments are done to build a geodesic dome out of bamboo. Different types of connection components are used to join the struts. One of the projects is by Aakash Kushwaha as a part of the course in Indian Institute of Technology, Delhi. He built a bamboo geodesic dome using frequency 2V. In a 2V dome, each equilateral triangle is divides into 4 triangles. This results in two types of struts varying in length.
Two different kinds of joineries were designed and tested for the dome. The span of the dome is 6m. A total number of 65 struts were used, resulting in 130 joints.

Another interesting bamboo geodesic dome is constructed by a company in Bangalore, India. This is again a 2V frequency dome. But it has a double layer of framework. The framework seems to be pre-tensed which increases the rigidity of the entire structure. The struts in both the layers of the framework forms a subtle bow, which tapers alternately at the subdivisions. The double layer bamboo is bent and tapers towards the nodes. This gives a fish belly shape appearance (Wondergrass.in, n.d.). A similar concept is used by Marcel Kalberer for bamboo folding umbrella. The columns are made of curved interconnected bamboo poles (Minke, 2012). This pre-stressing of bamboo helps to counter the horizontal loads and minimizes deflection (Larsen & Tyas, 2003).

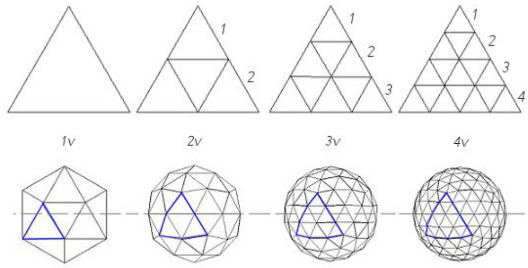


Figure 4.4a: Frequency of geodesic dome.


Figure 4.4b


Figure 4.4c


Figure 4.4d


Figure 4.4e

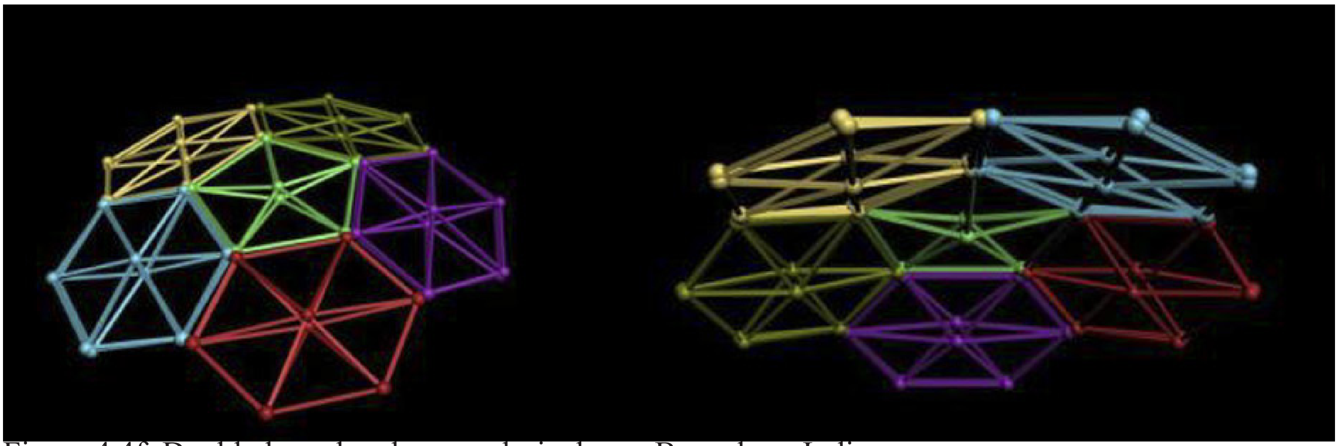


Figure 4.4f: Double layer bamboo geodesic dome, Bangalore, India.


Figure 4.4f: Bamboo folding umbrella, Marcel Kalberer

4.5 NAMAN RETREAT- VO TRONG NGHEIA

This bamboo vault is another lightweight, sustainable structure by architects Vo Trong Ngheia. It is a conference hall, which is part of a resort. The structure for this arched vault is made entirely of bamboo. The columns continue up to form the arch. An arch is formed by intersection of two half arch which is an extension of the columns on both sides of the hall. Two types of bamboo are used for this project. Luong bamboo, is strong and durable used for the straight columns. While Tam Vong bamboo is flexible and used for the curved arches. The height of the columns is 8m and overall roof height is 9.5m. There is a 4m wide corridor which is also made of bamboo vault adjoining the main hall. The main hall spans 13.5m.

The column and arches are bundled together using bamboo ropes. The entire length of the structure is supported by 20 such arches and columns behaving like trusses. The bundled columns bifurcate into four different elements: main arch, secondary arch on which the roof directly rests, half arch and straight columns. All these elements directly or indirectly support the roof. The roof is made of local thatch layer with horizontal bamboo supports below. In between the columns, when it bifurcates horizontal ties are inserted which retains the arched shape of the structure and adds rigidity. The base of the pillar has more number of bamboo canes. Not all canes continue to form the arch. Again when two arches from both side intersect, additional bamboo canes are inserted and then tied together. This helps to avoid movements between the two arches.

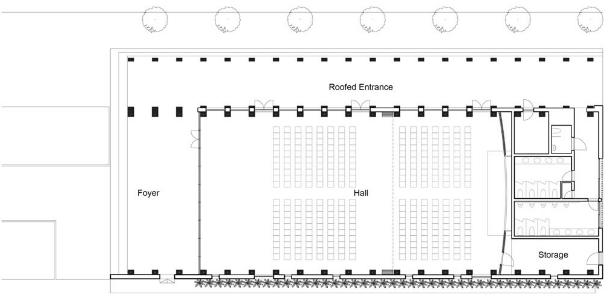


Figure 4.5e: Floor plan

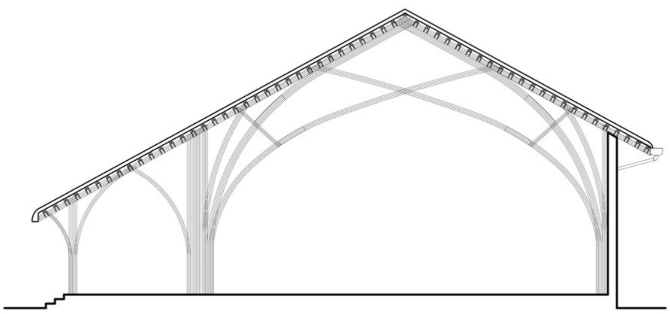


Figure 4.5f: Cross section


Figure 4.5a


Figure 4.5b


Figure 4.5c


Figure 4.5d

A segment of the vault is replicated in an arch form and compared with a straight line truss. Deflections occurred in truss are more than the arched-vault. Because of pre-stressing the beams, deflections occurred are lower than in straight beam truss. As the forces are transferred by the arched elements in compression.

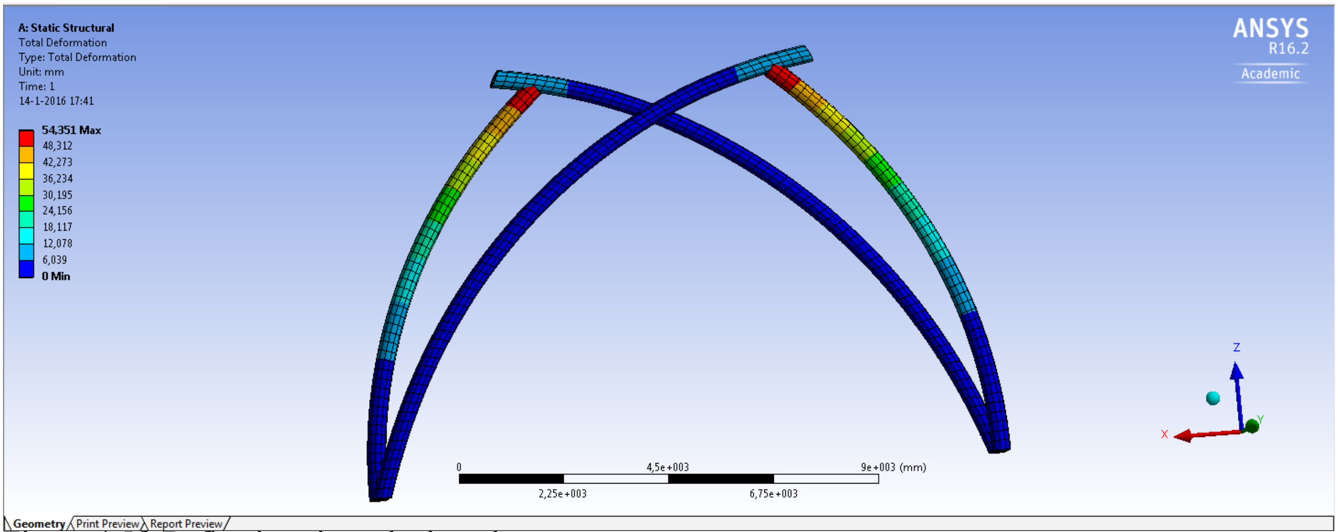


Figure 4.5f: Deflections in arched-vault.

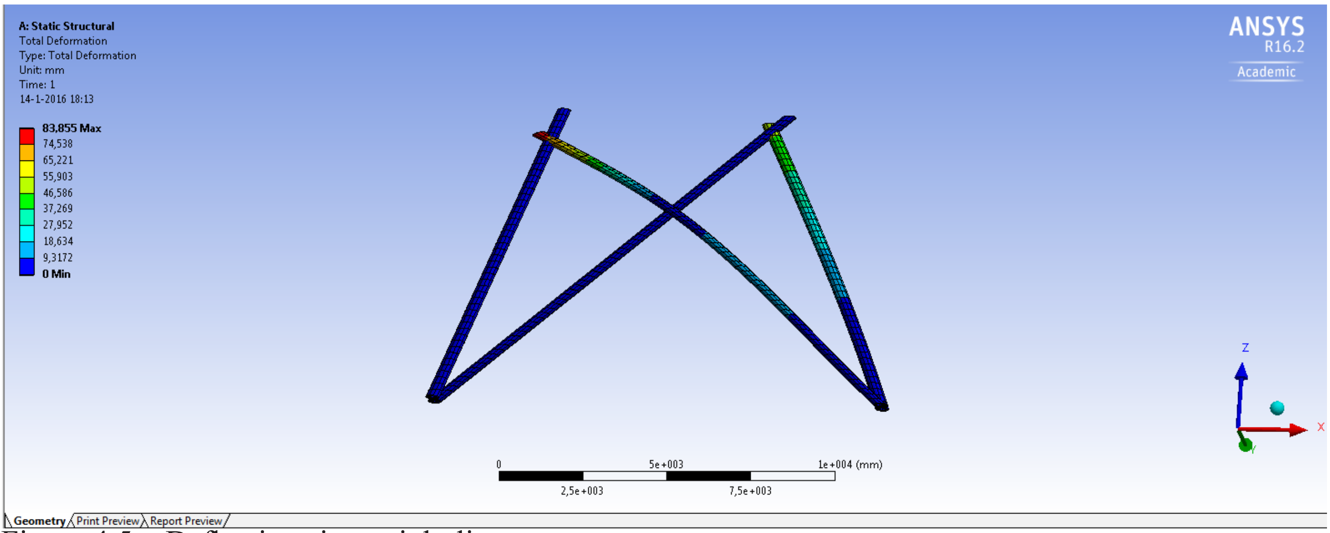


Figure 4.5g: Deflections in straight line truss.

4.6 BAMBOO PRECEDENT COMPARISON

	Ecological Center	Zeri Pavillion
Geometry type	Hyperbolic Paraboloid Roof	10-Sided Polygon Roof
Span	26 M	40 M
Height	7 M	14 M
No. of types of elements	2	2
Total no. of elements	24 Divisions 4 Edge Beam	24 Diagonals 10 Ring Polygons
Elements straight or curved	Curved	Straight

Community Center	Geodesic Dome	Conference Hall
Half Dome	Dome	Vault
25 M	6 M	13.5 M
12.5 M	3 M	9 M
3	1	2
24 Meridians 14 Latitudes	65 Struts	20 Arched vaults
Curved	Straight	Curved

JOINERY SYSTEMS

5

5.1 BAMBOO CONNECTIONS

Bamboo has been used for scaffolding and temporary structures since many years. For these structures simple tying or lashing methods are used as connections. But lately architects, designers and engineers have taken interest in building permanent structures from bamboo. Hence, the connections have been modified and more sophisticated joineries are developed. But further research needs to be carried out as every type of connection system has some advantages and disadvantages to it. It is important to design a suitable connection depending on the kind of forces the structure has transfer from one element to another. Although bamboo has good tensile strength, it has a low shear and splitting strength. Hence developing the connections becomes challenging. It has been observed that the elastic property and tensile strength reduces radially (Villegas, Morán & García, 2015). When loaded, the culms develop longitudinal fissures. The connections should be able to transfer forces without any local stress concentrations. Because of this failure, the structure fails before it reaches the longitudinal strength of the material. The hollow tubular structure of bamboo makes it difficult to connect it with each other unlike wood. Bamboo is not a homogeneous material; as a result the position of the joints needs to be pre-planned. In the internodes, the fibres of the bamboo are in longitudinal direction. The chance of splitting or fatigue appearing is greater in this region as compared to in the node region. This is because the fibres are in random direction in this region preventing from splitting.

Different case studies will be discussed for further understanding of the joinery system. These connections will be studied in terms of force transfer, material and labour required, weight of the components, failure mode and flexibility of the connection (able to use one type of connection in different ways). Inspired by these assembly systems, a new type of joinery will be proposed accommodating thin glass for cladding.

LASHING CONNECTION

Figure 5.1a: Lashing joint using bamboo cane rope.

Figure 5.1b: Lashing joint coated with epoxy resin.

Figure 5.1c: Rope passed through slotted bamboo

Friction tight ropes are used to connect bamboo poles to each other. Different knots have been developed to connect bamboo at different angles. Natural as well as synthetic materials are used which include ropes made of bamboo canes, coconut fibres, stem of palm trees, galvanized wire and dampened leather so it tightens as they dry (Minke, 2012). Ropes can also pass through pre-drilled holes in bamboo. But these tight ropes deform plastically over a period of time. They loosen up the joint, which lead to an overall failure. The optimum way to transfer forces is to have complete contact of bamboo elements. When using a tying connection, only the tangential surface the poles are in contact. Also the outer surface of the bamboo is smooth forming a frictionless joint, which is not bonded well together. When using a drill hole tying technique, if the rope is too tight it will tend to split the bamboo culms. On the other hand if the rope is loose it will not be able to transfer forces to connecting members. Another way to strengthen the stiffness of the rope and protect it from moisture is to coat with epoxies (figure 5.1b). The durability of the joint improves with resin coating. However, this coated joints restricts bamboo to expand and contract, which will create local stress and propagates cracks.

PLUG-IN DOWEL CONNECTION

Figure 5.1e: Wooden dowels passed through slotted bamboo

Bamboo is drilled and wooden dowels are inserted in it. These dowels indirectly connect bamboo canes. The dowels are joined with mortise and tenon joint. To achieve a good contact between the two poles, one edge of the pole is shaped like a fish mouth. This forms a groove, which holds the other bamboo pole. It maximizes the contact surface between the two pole, transferring forces efficiently. But it is difficult to achieve different angled connections, as developing exact fish mouth groove contact is difficult. Also inserting the dowels and connecting it with each other at an angle will be challenging. This joint is suitable for perpendicular connections.

CEMENT INJECTION AND BOLTED CONNECTION

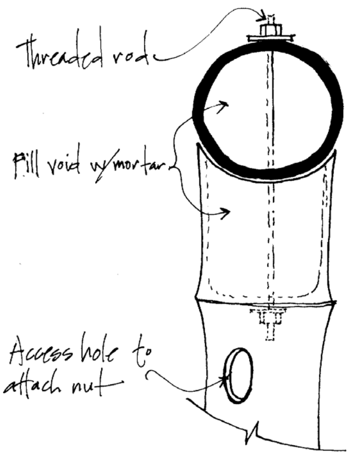


Figure 5.1f: Fish-mouth joint, Simon Velez

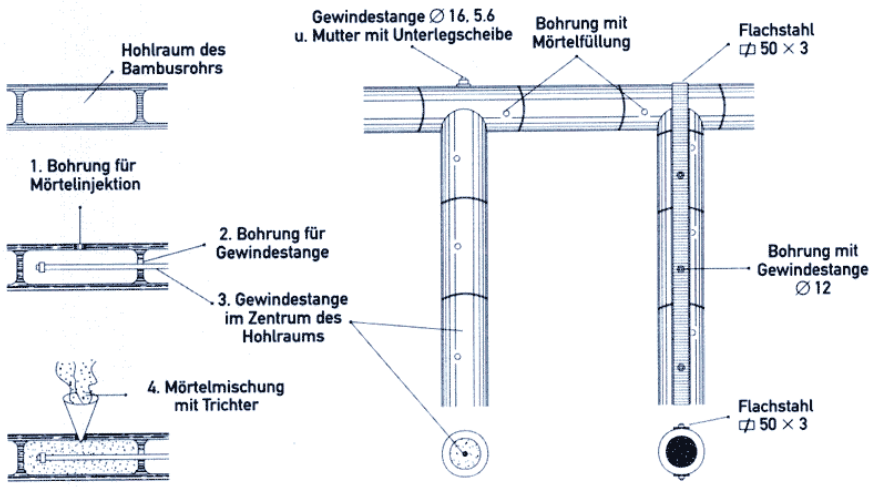


Figure 5.1g: Mortar reinforcement, Simon Velez

When bamboo is subjected to loads, joints become vulnerable and tend to split. Hence reinforcement is required to locally strengthen the material. This also further helps in transferring forces as the surface area through which the force is transferred increases. One or two nodes are drilled and a thread pole is passed though it. The internode region where the thread pole ends is punctured to screw the pole using a nut and a washer. Mortar is then injected from outside (Rottke). Depending on the angle of the adjoining member, the wall of the bamboo is punctured and thread pole is passed through it. Cement mortar with plastifying additive should be used to improve the fluidity of the mixture (Minke, 2012). If the ratio of the cement mortar mixture is not appropriate, it will shrink during drying and cause premature failure. Although this type of connection is less labour intensive, the bond between the mortar and bamboo fibres is critical. The joint under excessive and prolonged tension will fail as the adhesive bond is limited. Another disadvantage is the added weight to the element and negates the purpose of using a lightweight material.

WOOD PLUG CONNECTION BY ARCE, 1991, TU EINDHOVEN

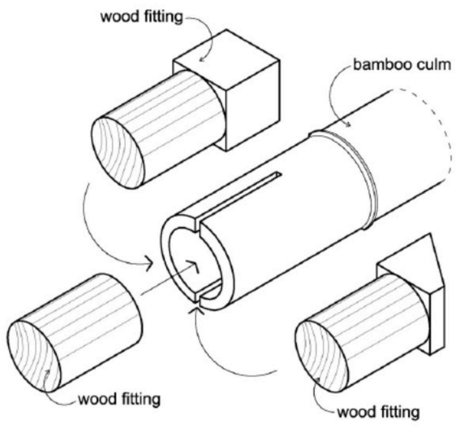


Figure 5.1h: Wood-plug joint, Arce-Villanobos

A wooden cylindrical piece is inserted in the bamboo culm. This wooden plug behaves as an extension of bamboo and distributes loads axially. The end of the wood can be connected to the adjacent member (at any desired angle) like a standard timber joint Before inserting the wood, the inner circumference of the culm needs to be even out using a sand paper. This is done as the size of the inner diameter is not constant (Arce,1993). After sanding, the wooden plug is fixed using adhesive. Like the cement injection joint, if appropriate glue is not used, the wooden plug will tend to slip out.

STEEL LASHING JOINT BY WIDYOWIJATNOKO, 2012 ,RWTH AACHEN

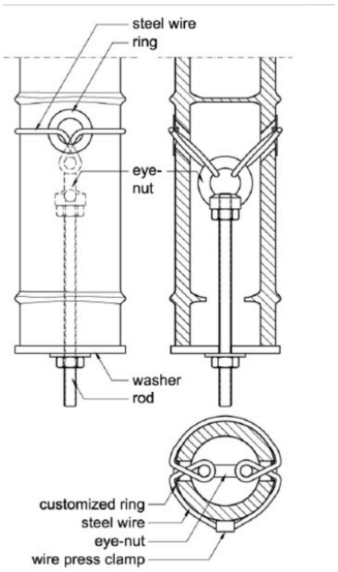


Figure 5.1i: Lashing joint with eye-bolt, Widyowijatnoko


Figure 5.1j: Lashing joint experimental model


Figure 5.1k: Eye-bolt

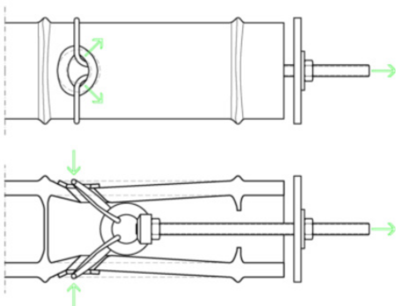


Figure 5.1l: Lashing joint, force transfer

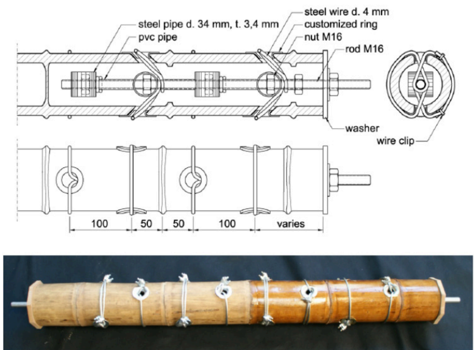


Figure 5.1m: Multi-knot lashing joint, Windyowijatnoko

Widyowijatnoko proposed a joint system, which uses the property of bamboo to its advantage. He developed a steel wire lashing system, which transforms axial tensile force into compression force (Widyowijatnoko, 2012). This tensile connector transfers forces into compression force on the outer wall of the bamboo culm, which is the stronger part of bamboo. The strength of the bamboo decreases radially, from outside to inside due to fibre content. Metal rings are attached to the culm and wire is passed through it (figure 5.1j). This wire is connected to the threaded rod which in turn can be connected to a metal component for assembling one or more members. The assembly is not susceptible to splitting like in case of bolted joints. This is because the wire is connected to the culm in such a way that pulling force increases radial compression and prevents from splitting (figure 5.1kl) (Widyowijatnoko, 2012). This type of connection is suitable for culm with varying diameter and thickness. Problems related to bonding of adhesive or cement doesn't exist, giving a lightweight mechanism. The disadvantage is that the rings and end components needs to be custom made depending on the type of connection. Under excess tension the ring may slip into the hole, causing the wire to slice the culm. Due to excessive compression on the outer wall surface of bamboo can lead to ovalization. This can be prevented by using steel components and wires, which will fail in ductile yielding prior to bamboo culm ovalization. The joint predictability is higher because of constant steel properties compared to bamboo properties, which keeps differing.

METAL SUPPORTED BUTT JOINT

Figure 5.1n: Metal end supports, Marcelo Villegas

Figure 5.1o: Connection using end supports, Marcelo Villegas

Figure 5.1p: Fixing using end supports, Marcelo Villegas

Figure 5.1q: Rubber end supports, Adan Piza

Figure 5.1r: Connection using rubber end supports, Adan Piza

Metal support connection systems have been developed by Marcelo Villegas (Minke, 2012). This is an alternative solution to fish-mouth joint at the end of bamboo poles (figure 5.1o). Instead of carving and shaping the bamboo to form a butt joint, metal components are shaped as butt joint to distribute pressure to the canes. As a result, equal pressure is distributed from screws to canes preventing stresses. This joint behaves well in compression and unlike bolted joints, which is prone to splitting. Adan Piza developed a similar component but made out of rubber (Minke, 2012). This behaves more adequately in distributing pressure. Also corrosion and rust from metal connectors are avoided if rubber butt joints are used. The end of the bamboo cane can be fixed to metal either by bolting or using adhesive. And the butt joint to bamboo surface should be bolted, as the joint will tend to slip if adhesive is used. The disadvantage is the metal or rubber connectors have to be custom designed.

METAL CLAMP CONNECTION

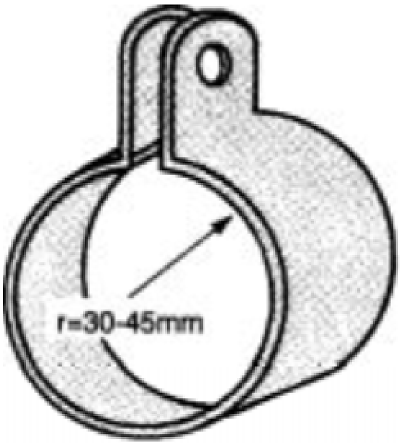


Figure 5.1s: Das clamp

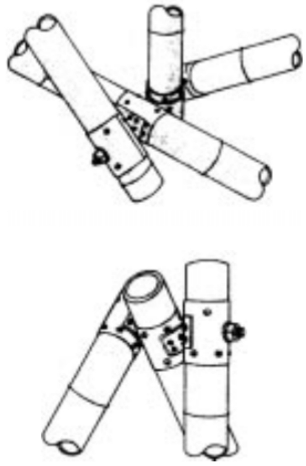


Figure 5.1t: Herbert shear pin connector joint

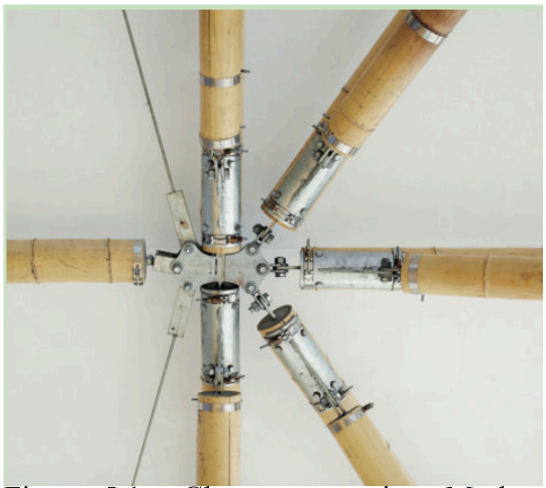


Figure 5.1u: Clamp connection, Markus Heinsdroff

To avoid bolting the culm, clamps are used for connections. The clamps have sleeves with integral bolt connection. Again, like the wire lashing technique the pressure is exherted on the outer surface of the culm, which is the strongest part (figure 5.1t). This prevents from splitting the culm but too much pressure can lead to ovalization of bamboo culm. Markus Heinsdroff developed an alternative for German Pavilion in China, 2007 (Minke, 2012). He used clamps not for connections but for anti-splitting action (figure 5.1u). The end of the canes are bolted with steel components and the internodal region is clamped. At the UK Building Research Establishment, Herbert shear pin connector was developed (figure 5.1t). This method also uses clamp. The culms are bolted together using thin gauge steel sleeves, which are pined to the clamps. The sleeves help in transferring the load to the bamboo. This joint is not a fixed joint, allowing moments and might prove to be unstable. In-plane connections are not possible. Other methods of joining suggested binding instead of pinning and the sleeves could be integrated with teeth.

5.2 GLASS CONNECTIONS

BOLTED/HOLE CONNECTION

Holes are cut in the glass either by drilling or by water jet cutting. Compared to drilling water jet is a safer method, as it does not damage the surface of the glass so much. This connection is not recommendable as it creates high local stresses. Post processing like tempering is not possible on the sides of the hole. It also becomes difficult to connect with other layers of glass with lamination.

Figure 5.2a: Bolted connection.

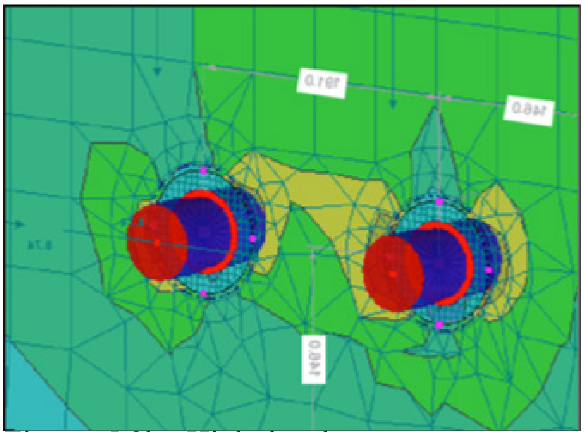


Figure 5.2b: High local stresses on glass around holes

LAMINATED CONNECTION AND GLASS INSERTS

Glass lamination is a process by which glass sheets are interconnected by foil. It is done with PVB (Polyvinyl Butyral) or SGP (Sentry glass Plus). With PVB, glass sheets are bonded together under high pressure and temperature in an autoclave. Sentry Glass foils are available in various thickness 0.89mm, 1.52mm, 2.28mm. SGP has 5 times higher tear strength than PVB. It is more rigid and does not propagate cracks easily. The advantage of using lamination is that it increases safety of the glass. It holds the glass layers together even if one layer breaks. Apart from connecting glass-to-glass, metal inserts can also be laminated to glass. Metals like stainless steel, soft aluminium, titanium can be laminated with glass.

Figure 5.2c: Lamination with PVB film

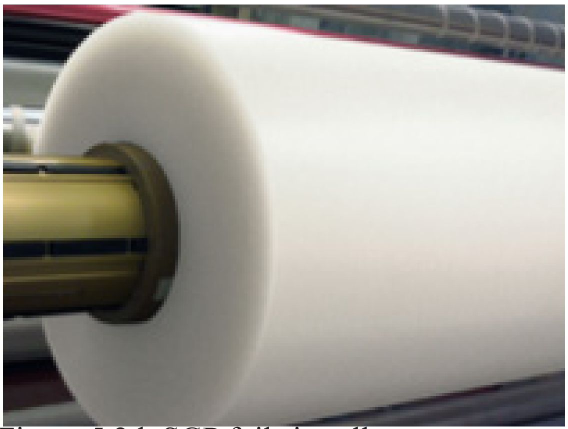


Figure 5.2d: SGP foils in roll.

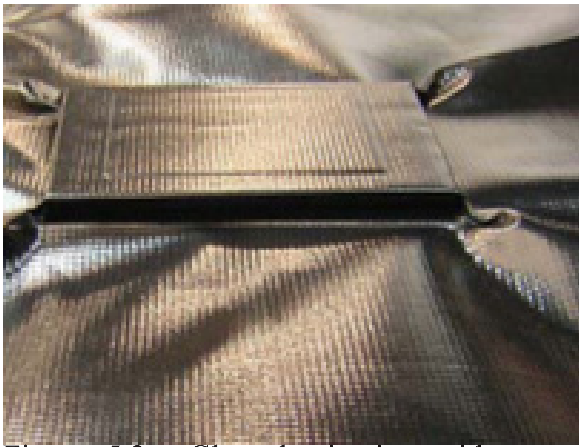


Figure 5.2e: Glass lamination with SGP, vacuum bag process

ADHESIVE BOND

Adhesive bond is widely used to fix different materials or same materials together. While using an adhesive bond, it is important to consider the type of loads acting on the material, geometry of the material and composition of the material. The type of connection in most cases is rigid. Load carrying ability is both in tension and compression. Because of adhesive bond, the size of the connection is smaller, creating less visual obstruction and reducing local stresses in glass.

The strength of the bond compared to some mechanical support is low. Many parameters can reduce the strength of the bond like weather conditions, surface treatment and loading type. The joint has to be done in a conditioned place; hence on site development is not possible. Curing time plays an important role. There cannot be any movements of the elements bonded which will weaken the bond. It requires special skills while handling and applying adhesive bonds.

There are many types or brands of adhesive:
- acrylic: for structural, reinforcement, automotive.
- anaerobic: for mechanical, medical, automotive.
- cyanoacrylates: for precision industry.
- epoxy: for structural, aerospace, buildings, transportation.
- polyester: structural.
- polysulfide: sealant for wood, concrete, metal, glass.
- silicones: sealant in buildings, automotive industry, aerospace.

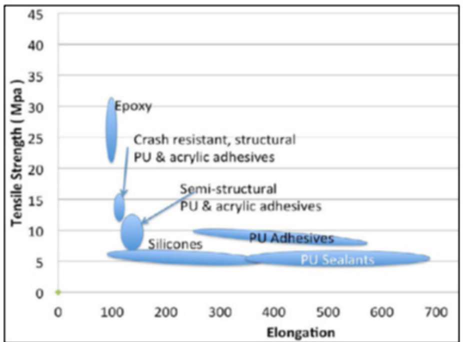


Figure 5.2f: Tensile strength of adhesives

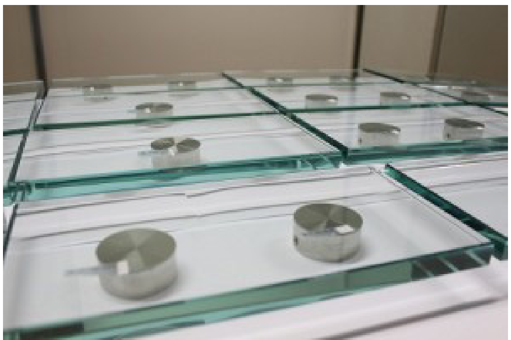


Figure 5.2g: Metal components bonded to glass with adhesives

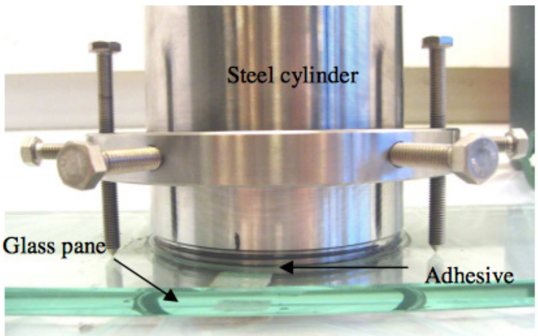


Figure 5.2g: Testing adhesive bond strength

BENDING PROCESS

6

6.1 BAMBOO BENDING

BENDING WITH WATER

Bamboo poles are soaked in lukewarm water overnight. Depending on the size and thickness of bamboo, it requires more soaking period. Bamboo behaves similar to wood in bending. Like wood it requires moisture to bend. This helps to soften the lining and hemicellulose in the bamboo cells and allows it to flex. Dried bamboo molecules are crystallized which becomes difficult to bend. After soaking the bamboo, slowly bend the pole into the desired shape. If there is a cracking sound then it needs to be soaked in water for a longer duration. The exact curve can be achieved by creating a formwork using nails. Nails can be hammered on to a plywood sheet, forming concentric curve shape. Then moist bamboo pole are inserted between these two layers of nails and bent along the curvature. Instead of using nails, wooden blocks with the required curvature can also be used but that will be a lot of waste of materials if different curvatures are required.

Figure 6.1a: Formwork of bamboo using wood plugs and nails

BENDING WITH HEAT

This is a more advanced method commonly used by artisans. The nodes in the bamboo poles are removed using a re-bar. This process is labour intensive and time consuming. The nodes are removed so that the poles are filled with sand to avoid splitting of the walls while bending. Another method to fill the sand is drilling holes in the internodes and using a funnel to fill sand inside it. Vapor holes are required for excess heat to escape from bamboo. Using a flame torch, bamboo is heated. Heat is applied in the direction the bamboo grows, i.e. from the broadest to the narrowest section. With heating, lignin and pectin becomes soft and pliable, allowing to mold easily (Bamboo, n.d.). Along with bending, heating bamboo gets a stain, which gives it a warm look. To check the flexibility, wet rag is swiped down the pole and bent. Before bending the bamboo, sand is filled so that the walls don not buckle while bending. Bamboo is heated and simultaneously curved at intervals. Heating should be concentrated on the areas where maximum bending is required. The pole is wiped with wet rag periodically. This prevents the bamboo from drying and becoming brittle which leads to splitting. This process of heating, bending and dampening the pole should be repeated until the desired curvature is achieved. The process has to be gradual to avoid splitting as stresses are applied while shaping the bamboo.

Figure 6.1b: Heating bamboo with flame torch and

BENDING WITH SPLIT

Bamboo is split at intervals, using a knife and the bent. The split is in the for of v-shaped which is cut near the nodes. The angle of the cut depends on the angle of the required curvature. If the bend is slight then the cut is narrow and if the bend is sharp then the cut is wider. Even the depth of the cut depends on the curvature. Cuts can be shallower if the bend is not much. The maximum depth of the cut can be two-third diameter of the poles. Depending on the size of the bamboo and the desired curvature, adjacent grooves are split. After bending the bamboo, it needs to be secured using a lashing or an adhesive so that the bamboo is set in place.

Figure 6.1c: Splitting and bending the bamboo

BENDING WITH STEAM

Bamboo poles are placed in a well insulated steam box, usually the interior of the box is made of aluminium and exterior is made of wood. The box has an opening to insert the pipe from which steam is blown. Depending on the size and thickness of the bamboo, steaming is required (approximately 2 hours). After steaming, the lignin becomes soft and the pole can be bent. Bending according to the required curvature can be done using formworks as explained in method 1.

Figure 6.1d: Bamboo cured in steam box.

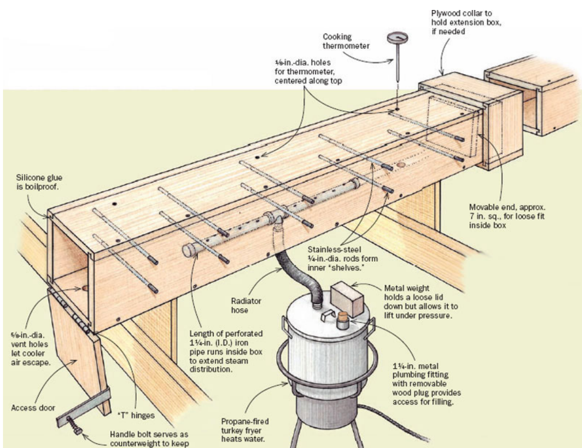


Figure 6.1d: Wooden steam box.

6.2 GLASS BENDING

HOT BENDING

Glass curving or shaping cab be done by thermal treatment. In this process the glass is deformed permanently. Flat glass is heated at a temperature of 550°C to 660°C. At this temperature range, glass softens and deforms accordng to mould or pressure applied. There are three different methods to hot bend glass:

In line bending: This technique is mostly used for developable cylindrical surface. It is a two step process, where first glass is heated then deformed by two parallel adjustable quench devices. This has moving chords with cooling nozzles. Glass cools fast with the help of these nozzles which permits pre-stressing of glass. Conical shape glass can also be achieved with this method.

Gravity (sag) bending, slumping: Glass is deformed by gravity using a custom made mould. The mould is used to define the glass shape partially or completely. It is possible to obtain a single or double curved form. Two stacked glass can be moulded simultaneously. Hence this allows curved glass suitable for lamination. Following bending, glass is slowly cooled deforming it plastically.

Press bending: This method is mainly used for curved automotive glazing. Glass is thermally curved using press and blow process. Pressure is applied using a mould and the glass pane is supported using a hollow ring mould. Double curved glass can be formed with this process. Fast cooling can also be done to obtain heat strengthened or toughened glass.

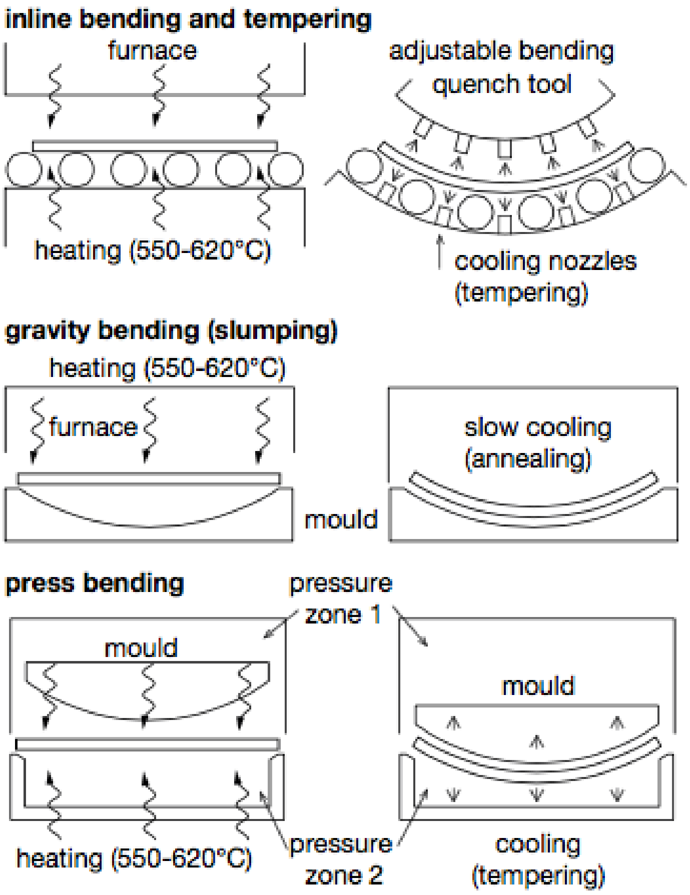


Figure 6.2a: Hot Bending of glass with different techniques
ref: (Fildhuth, 2015)

COLD BENDING

In this process, glass is bent at room temperature using mechanical pressure. Unlike hot bending, glass is bent elastically. Shape is preserved either by clamping it or by lamination. Only developable surfaces can be derived from this method. Compared to hot bending the curvature obtained is lower as glass is bent in its solid state. The optical quality is not hampered with this process. Whereas in hot bending optical clarity is not the same after process.

For lamination of glass, interlayer of polymer material like poly-vinyl butyral (PVB) or high shear stiff ness ionomer (SG) can be used. The glass needs to be laminated first before cold bending it. Alternate layers of glass and PVB are stacked together and placed in a vacuum bag. Inside the vacuum bag, the glass is placed over a mould and bent by applying pressure at the ends. The bent glass is fixed in position by applying temporary supports at the ends. The whole set up is laminated in an autoclave. This process involves simultaneous pressure, temperature and vacuum. After cooling, the temporary supports are removed. Glass undergoes an initial spring back. For relaxation period glass is placed on the curved edges to minimize the effect of its own weight. When lamination is used in order to retain the shape of cold bent glass, it experiences creep over a period of its service life. This is because of the visco-elastic behaviour of interlayer.

Stresses are induced while bending or curving the glass. Hence it is important to check the curvature of bent glass. Lower radius while cause high stresses. The stresses developed due to cold bending should be lower than the ultimate limit strength of the glass.

Figure 6.2b: Cold Bending of laminated glass in vacuum using aluminium mould
ref: (Fildhuth, 2015)

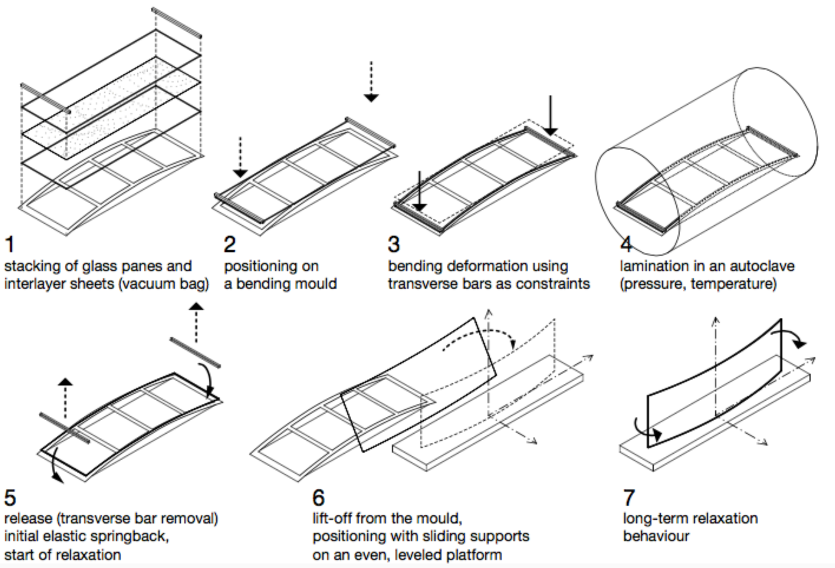


Figure 6.2c: Cold Bending of laminated glass
ref: (Fildhuth, 2015)

SHELL STRUCTURES

7

7.1 THEORY OF SHELLS

A surface, which is curved in one or more direction falls under the category of shell. Single curvature shells are curved in one linear axis. The application of shell is widely seen in not only architecture but also transportation and appliance industry. Body of aircraft, cars and even space engines are common examples. However in architecture, the earliest forms of shell structures are seen as domes and vaults with large spans. With the invention of new materials (steel, concrete, metal) and manufacturing technologies, shell started developing with exploration of new forms and geometries.

A shell is made up of curve elements. These curves are infinitely gradient i.e. they all have different radius of curvature. According to the kind of gaussian curvature (k) the shell has, it can be classified into three main categories:

- if $k > 0$ then it has a positive gaussian curvature and is called clastic surface.
- if $k = 0$ then the gaussian curvature is neither positive or negative.

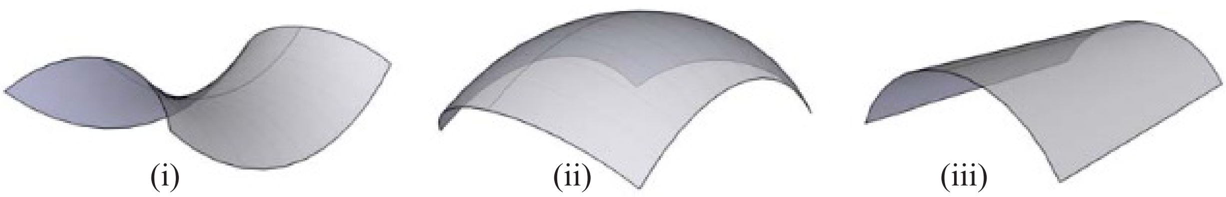


Figure 7.1a: (i) negative, (ii) positive and (iii) zero gaussian curvature surfaces.

Single curvature and double curvature are terms only used to compare the rigidity of the surface and the complexity of centering necessary to construct the shell form. But the most important character is the method of surface generation.

- Surfaces of revolution: Surfaces are generated by revolution of a plane curve about an axis called the axis of revolution. The revolving curve that forms the surface is called meridional curve. Examples of these surfaces are cylinder, cones, spherical or elliptical domes, hyperboloids of revolution, toroid. In some cases line cylindrical and conical surfaces the meridional curve is a straight line.

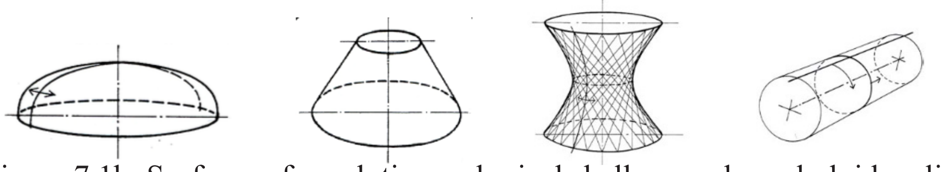


Figure 7.1b: Surfaces of revolution: spherical shell, cone, hyperboloid, cylinder

- Surfaces of translation: Surfaces are formed by sliding one plane curve along another plane curve while keeping the orientation of the sliding curve constant. The curve on which the original curve is slided is called the generator of the surface. In some cases the generator is a straight line and the resulting surface is called a cylindrical surface.

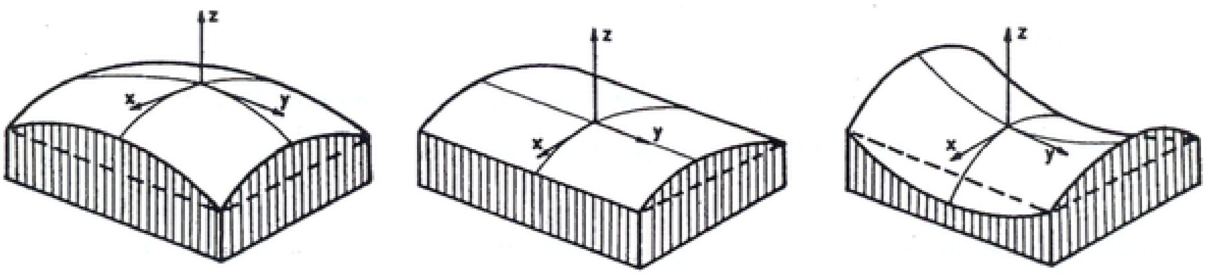


Figure 7.1c: Surfaces of translation: elliptical paraboloid, cylindrical paraboloid, hyperbolic paraboloid.

7.2 SHELL BEHAVIOUR

The most important feature of shell is its small thickness to span ratio, which interests designers and engineers. The shells must be thick enough to avoid buckling. Large spans are possible with minimum material. Shell structures have proved to be much stiffer than a flat plate as they rely on more efficient load carrying mechanism (Miura and Pellegrino). What makes this possible is the unique way of distributing load. This behaviour of shell is called membrane action. Membrane action results only in normal in-plane shear stresses Nx, Ny, Nxy (figure 7.2a). These stresses are distributed uniformly over the cross section. Bending stresses are small in compared to the in-plane stresses and negligible. Hence the basic assumption of membrane theory is that in a distributed load only pure membrane stress fields are developed. Because of the initial curvature, shells can resist in-plane forces and out of plane loads by membrane action. If supported properly, the stiffness of the shell is only because of the membrane action.

So for a given shell the membrane in-plane stress distribution is in equilibrium with the load. But this theory does not apply in certain conditions when:

- The deformation of the shell does not satisfy geometric compatibility where there is discontinuity in shape or curvature especially near the boundaries.
- The thickness is not even throughout and discontinuity in loading.

For these reasons, there are limitations in approximation of membrane theory and should be eliminated by considering both membrane theory and bending effect (figure 7.2b) in shell.

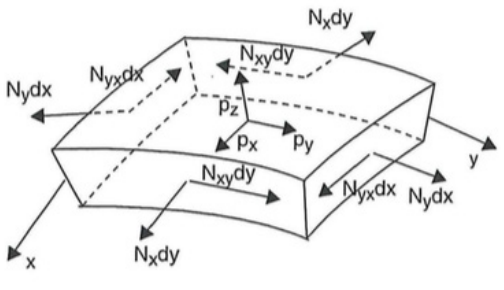


Figure 7.2a: Stress resultants with membrane action in shells.

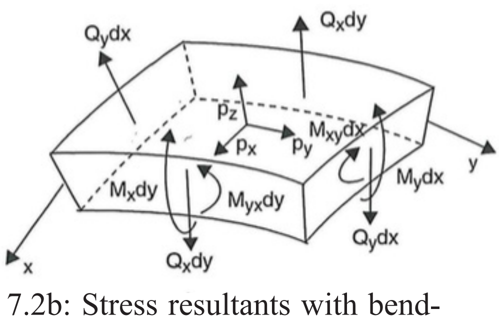


Figure 7.2b: Stress resultants with bending action in shells.

7.3 LATTICE SHELL STRUCTURES

As opposed to continuous surface, lattice structure is in the form of network of elements. These skeletal structures are new generation of shell structures, which started developing with invention of new materials. The main reason to shift from surface shells was economy of construction. The stability of the gridshell is still geometry dependent like surface shell structures. But the force distribution is different. The internal forces are transferred only through lattice elements and therefore the flow of forces is restricted. Lattice shell can only resist forces in the direction of lath i.e. axial forces. Continuous shells can resist normal and shear forces (figure 7.3b).

Like any other shell structure, a variety of forms are possible. But finding the shape of the geometry is not restricted to mathematical generation of surface systems and can be done experimentally. Mathematically, high degree polynomials can determine the surface shell geometry. Experimentally, the shape can be obtained by loading a chain or rubber membrane or a soap membrane, influencing the form desired by supporting at predetermined positions. The inherent nature of curvature will determine the stiffness of the gridshell. Hence it is possible to built it in a single layer. Double layer lattice shells are built usually to achieve large spans, the construction process becomes complicated and the structure may end up becoming heavy. Single layer latticed shells are structural systems with rigid joints while double layered lattice shells usually have hinged connections. Mostly single layer shells are seen in short span structure as they are prone to buckling if the span is too large. Along with axial forces, internal moments and torsion occur, if the span is too large and single layer latticed shell is used (Chen, 1997). The type of gridshell does not only depend on span but other factors like the geometry, size of the framework and section of the framework.

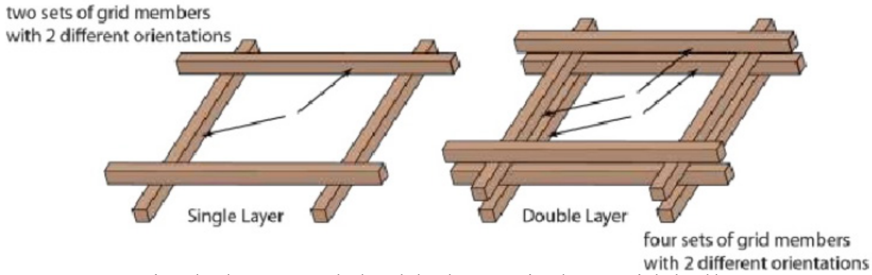


Figure 7.3a: Single layer and double layer timber gridshell

LOAD CARRYING BEHAVIOUR OF GRIDSHELLS

According to Happold and Liddell (1975), in continuous shells, the surface can direct forces and out-of-plane bending on orthogonal directions. But when considering elements of lattice shell, they can only resist force in direction of the lattice or laths along with out-of-plane bending. Therefore it cannot resist diagonal forces.

Double layer gridshell developed when structures had huge spans. This is because large span structures require higher resistance and stiffness to out-of-plane bending. Hence a higher second moment of area is required in the individual members, which means having thicker sections. But thicker the sections, it is likely to rupture during construction and curvature desired would not be possible. Hence to increase the second moment of area and stiffness double layer shells are used.

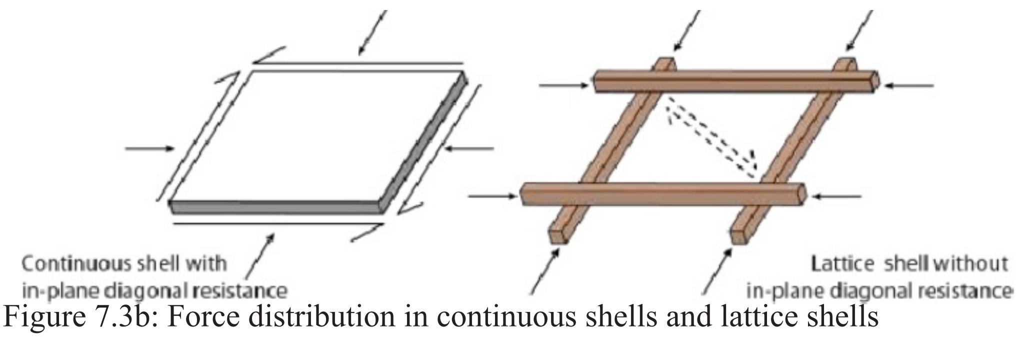


Figure 7.3b: Force distribution in continuous shells and lattice shells

CONNECTION SYSTEMS

As discussed before, elements of gridshells cannot resist diagonal forces alone. This means additional members are required. There are four ways in which diagonal forces can be countered (happold and Liddell 1975) (figure 7.3c):

- by introducing rigid joints at the nodes.
- by introducing diagonal cross ties.
- by introducing rigid cross bracing as equal cross sectional area to the grid members.
- by making sure the covering membrane is strong enough.

In case of double layered gridshell, there s a need to provide shear transfer between top and bottom layers (happold and Liddell 1975). As the two layers are connected at the nodes, shear force is automatically transferred in this region. Additional shear blocks are added between the two layers, leading to a composite section, which has greater strength (figure 7.3d).

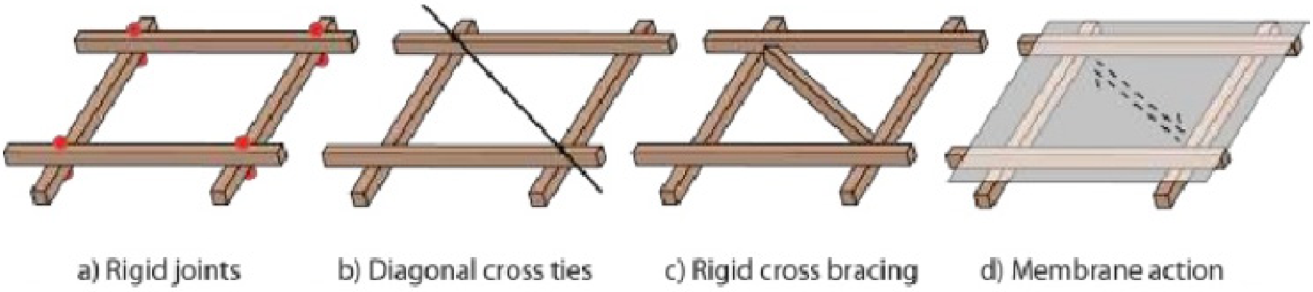


Figure 7.3c: Type of bracing systems

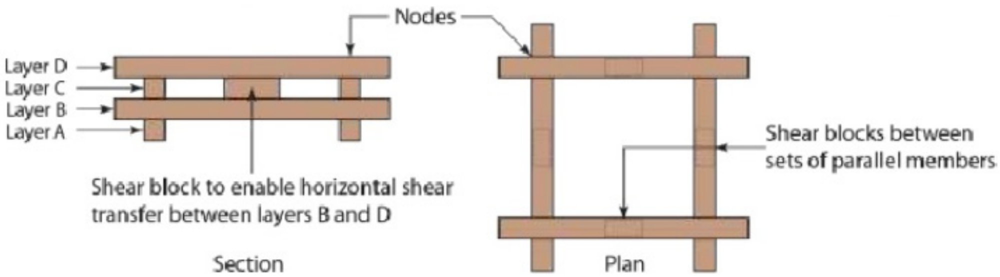


Figure 7.3d: Double layer gridshell with shear blocks

7.4 PRECEDENT

ESSEN PAVILION

The first gridshell was built in 1962 by Frei Otto. It was a temporary German exhibition at Essen. The structure was a dome with an elliptical base, measuring 15m in span and maximum height of 5m at the center. Built out of timber laths, shape of the dome as well as lengths required was determined using a suspended chain model.

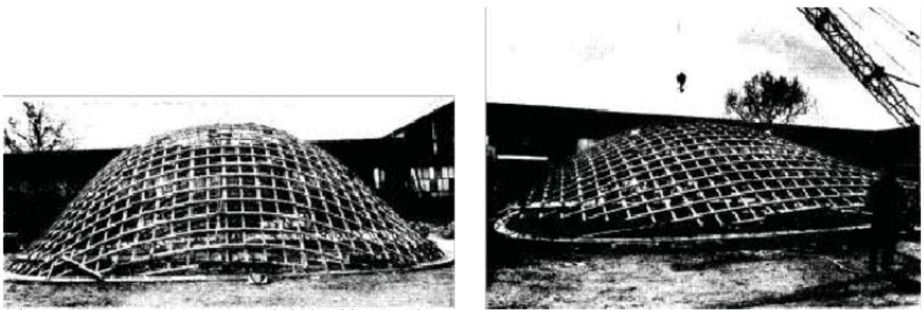


Figure 7.4a: Essen gridshell, Frei Otto

MANNHEIM MULTIHALLE

Another evolution in gridshell structure is seen in Mannheim Multihalle. This is a free form double layer lattice structure built for Federal German Gardening Exhibition in 1975. Architect Mutschler and partners along with Frei Otto were involved in designing and building this masterpiece. The span of the shell is 85m in length and 60m in width, with a height up to 20m. Such a huge scale shell structure was not attempted before at that time. True to the important characteristic of shell, the thickness is bare minimum compared to the span. The thickness of this gridshell is half a meter. The ratio of thickness to the span is 0.00625 and the ratio of thickness to mean diameter is 0.007. This shell can be categorized as a funicular shell. Funicular shell structures behave in pure compression. In this case, this is achieved by hanging a wire model which is in pure tension and then inverting it. This helped as gridshells are good in resisting axial forces but weak in resisting shear forces (which are perpendicular to the lathes). Strained timber laths i.e. curved lattice elements were used to build this gridshell.

The coordinates from the scaled model was obtained from stereophotogrammetry and used to visualize the actual scale (Shells.princeton.edu, n.d.).

Timber laths of 50mx50m were joined together, to form a 0.5m grid system. For resisting diagonal forces, at every 6th node, pairs of 6mm cables were used (figure 7.4c). The structure was clad with polyvinylchloride (PVC) reinforced and open-meshed polyester fabric. The structure had around 33,000 joints. At every node, four laths cross each other because of the double layer system. The shell was constructed using pre-forming method. That means the grid was first laid flat on the ground. By applying pressure upwards from inside and inwards from, the sides the final shape as per the design was obtained. In order to move and deform the laths, the nodal joints were bolted and kept flexible. After achieving the final form they were tightened and the laths were fixed to its position. And shear blocks were inserted to improve stiffness of the elements (as discussed in section 7.3).

Figure 7.4b: Aerial View Mannheim Multihalle

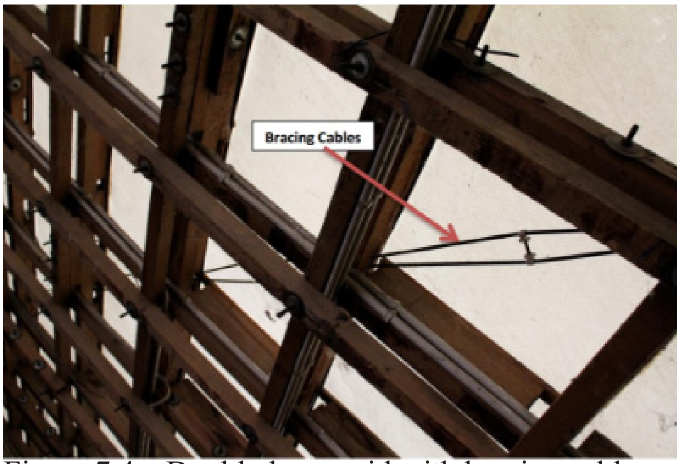


Figure 7.4c: Double layer grid with bracing cables

Figure 7.4d: Free form shell of Mannheim Multihalle

Figure 7.4e: Nodes bolted fixing

VELODROME LONDON OLYMPIC STADIUM

As seen in the analysis of case studies, structures which are made up of curved lattice elements have less deflection as compared to structures which are made of straight beam lattice elements. This is because of membrane action where bending stresses are limited. It is also evident in Velodrome Olympic stadium roof designed by Hopkins Architects. The structure has a hyperboloid roof. The primary structure of the roof consists of cable nets. The total area of the roof is 12,500m^2. It spans 131m length wise and 119m width wise. Because of the curved lattice cables, deflections are half compared to the straight lattice shell elements. This allowed long span curved profile cables for the roof with minimum deflections (Peter Debney, n.d.).

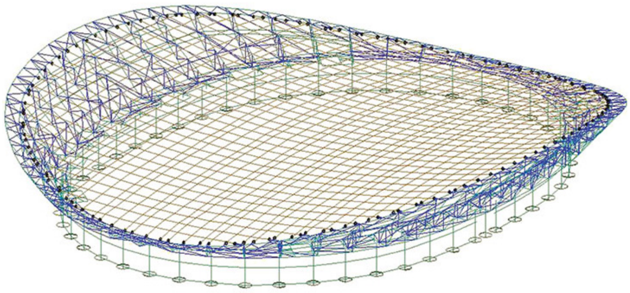


Figure 7.4f: Double curved cable roof


Figure 7.4g: Double layer steel cable grid

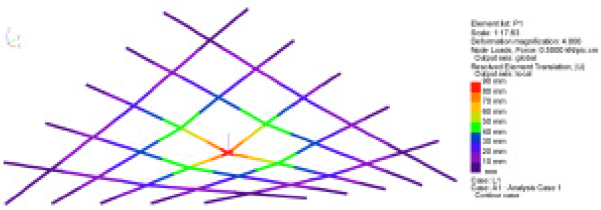


Figure 7.4h: Deflection of straight grid shell generator

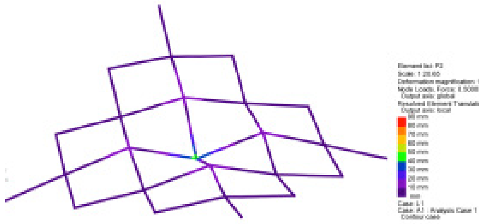


Figure 7.4i: Deflection of curved grid shell generator

The diameter of the cables are 36mm and form a grid of 3.6m. At the nodes 4 cables in pair cross each other, forming the hyperboiloid roof. Because of this configuration of pairing the cables, the size of the diameter can be less. The cables are connected using steel clamp nodes. They are made up of three elements which clamp the cables (top, middle and bottom plates) (figure 7.4j). These nodes also support the roof cladding system. The entire roofing system is so light and weighs approximately 30kg/m^2.

The form of the roof, maximizes the efficiency of the cables. The pre-stressed cables do not slack under SLS load combination. A pair of cable can take maximum tension up to 1340kN and does not vary much throughout the structure (Expedition Workshed, n.d.).

The cables are connected to a peripheral truss beam to transfer the forces. The upper part of the grid system resist gravity, while the lower network of cables resist wind uplift.

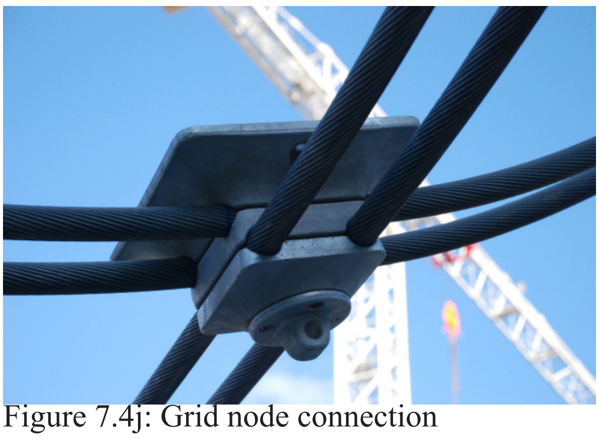


Figure 7.4j: Grid node connection

HYPERBOLIC PARABOLOIDS

8

Hyperbolic paraboloid or hypar is a recent form evolved in design and architecture compared to domes and vaults. Unlike domes generated by revolution of plane curve, hyperbolic paraboloids are double curved surfaces generated from transitional surfaces by sliding a plane curve along another plane curve. The orientation of sliding curve is constant. The curvature of hypar is anticlastic i.e. it has a negative gaussian curve. The early use of hypar surfaces in architecture has been used by architects Antonio Gaudi (1669), Bernard Lafaille (1933) , F. Aimond (1935), Giorgio Baroni (1934) (Schueller, 1996). But these were all primitive forms. After World War II, Felix Candela fully explored the potential of hyperbolic paraboloid. This is demonstrated in the magnificent church of La Virgen Milagrosa, built in 1955 in Mexico. The thickness of this concrete shell is 38-40mm (figure 8.1d). In Le Corbusier's Philips Pavilion series of hypar surfaces are arranged in a free form (figure 8.1e). The surfaces are generated from combination of linear and curvilinear elements (figure 8.1f). Initially hypar shells were constructed only out of reinforced concrete. Later on, because of the difficulty in building with concrete, grid shells came into existence. Steel and timber are extensively used to make shell structures and prove to be more economical and feasible.

Hyperbolic Paraboloids can be generated from straight lines, parabolic contours or hyperbolic contours (figure 8.1a). The important characteristic is its span to rise (height) ratio. The properties of hypar elements do not change if cut from location as shown in. Cutting the surface vertically gives parabola and horizontal section generates hyperbolas. By sliding a concave parabola (suspended cable) parallel to itself along a convex parabola (arch), hyperbolic paraboloid is developed. The concave and convex curves are perpendicular to each other. When curved elements are used, there is no bending force at the edges. The parbolic arches transfer axial components to the edges. Hence using curved elements in this case is more effective as lessconstructive materials are required comparatively.

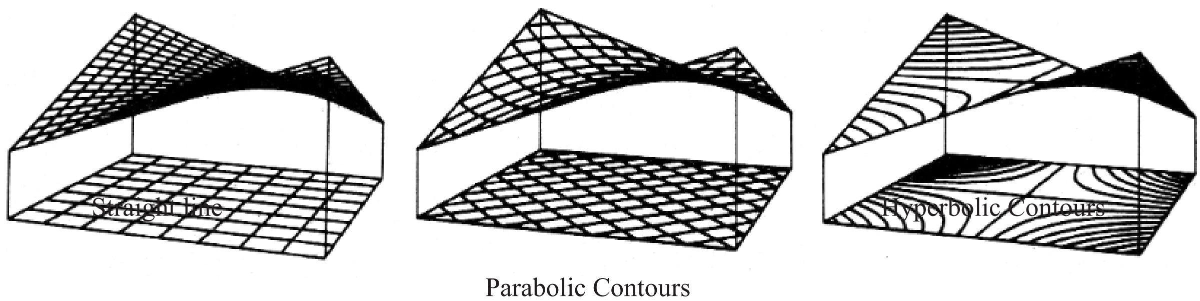


Figure 8.1a: Hypar shell generators

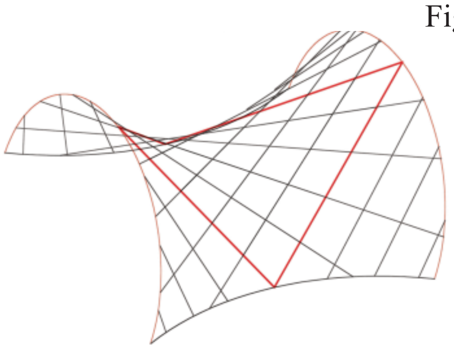


Figure 8.1b: Hypar surface part of hyperbolic paraboloid

A hyperbolic paraboloid is an infinite surface in three dimensions with hyperbolic and parabolic cross-sections. It is a doubly ruled surface shaped like a saddle. In a suitable coordinate system, a hyperbolic paraboloid can be represented by the equation:

$$\frac{y^2}{b^2} - \frac{x^2}{a^2} = \frac{z}{c}$$

For $c > 0$,this is a hyperbolic paraboloid that opens down along the x-axis and up along the y-axis (i.e., the parabola in the plane x=0 opens upward and the parabola in the plane y=0 opens downward).

The term hypar to mean a hyperbolic paraboloid shape, or more formally a partial hyperbolic paraboloid is cut from the full infinite surface (figure 8.1b, 8.1c). The term hypar was introduced by the architect Heinrich Engel, in his 1967 book Structure Systems (Erikdemaine.org, n.d.). Hypar shells transfers uniform symmetrical loading by tangential shear to the supporting edge ribs. The edge ribs should be place parallel to the form generators. Hence, the sum of the vertical component of the shear along the shell periphery is equal to the total load (Schueller, 1996).

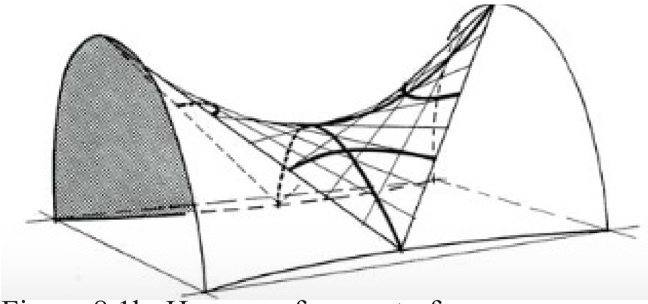


Figure 8.1b: Hypar surface part of hyperbolic paraboloid

Figure 8.1d: La Virgen Milagrosa, Felix Candela

Figure 8.1e: Philips Pavilion, Le Corbusier

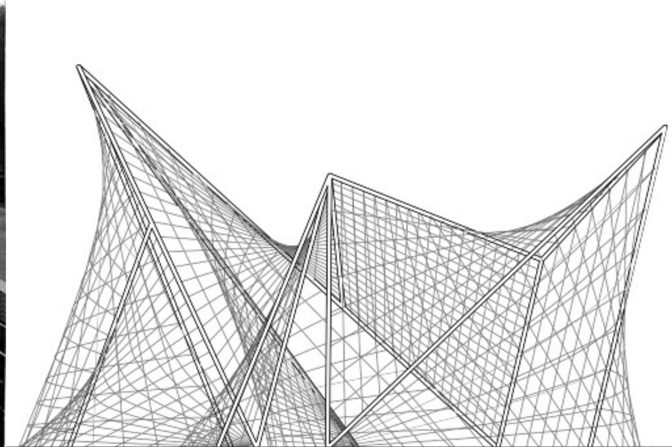


Figure 8.1f: Philips Pavilion, Le Corbusier

SITE INTRODUCTION

9

Conventional roof structure is replaced with lightweight sustainable material bamboo and thin glass. The site selected is a warehouse for a cardboard factory. It is located in Punjab, Northern India. The existing roof is made up of steel trusses and clad with corrugated aluminium sheet. As seen in the site images at intervals its is clad with polymer sheets allowing daylight. However this seems to be a post construction alteration and does integrate with the design. The length of the structure is 20m and the width is 10m with a height of 6.5m (at the valley). The climate in this region is hot and dry during summers from March to June, with maximum average temperature 38 ° C. It rains moderately during the months of July to September. Winters are from November to January with average minimum temperature 4-6 ° C.

The structure is mainly used to store raw materials used for cardboard manufacturing. Since the site is not habitable or the time people are going to be in it is only when they need to store or remove the raw materials. Hence insulation is not needed. But the goods should be well protected from rains, excess sunlight and insects. All these points are considered while designing the roof with bamboo and thin glass.

ROOF GEOMETRY/FORM

10

The roof structure is composed of 7 hypar shells. Hypar shells are part of hyperbolic paraboloid. These hypar shells are formed from pre-bent bamboo lattice elements. The decision to use pre-bent bamboo members is explained in Section 4. The hypar element is contoured to form parabolic curves. 4 hypar shells A,B, D,E have same span to height ratio (3.33). Shells C, F, G have span to height ratio (2).

The advantage of using bamboo and thin glass is, they have a good flexibility to strength ratio. The geometry of the roof is double curved and radius of curvature of all elements in one hypar shell are not the same. If some other material was used for the structure and cladding, each element would have to be customized and fabricated. However with bamboo and thin glass, the bamboo can be pre-bent plastically and glass can be pre-bent elastically and fixed to the position during construction phase. These arched curved (bamboo) and cylindrical curved elements (thin glass) can be achieved from same planar materials. This proves to be cost effect and less labour work is required. The other advantage of using this transparent glass is the it forms a waterproof layer on top of the bamboo, without visually dominating the bamboo gridshell

The roof structure is cantilevering on all sides up to 5m. This protects the interior bamboo structure from rain and sunlight, providing shade outside. The openings formed on the sides of the structure will allow to naturally ventilate the interiors.

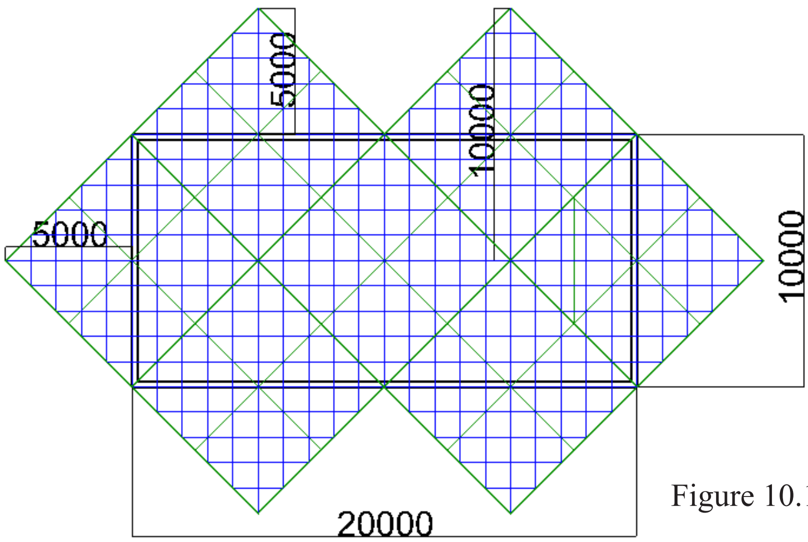


Figure 10.1a: Schematic Plan

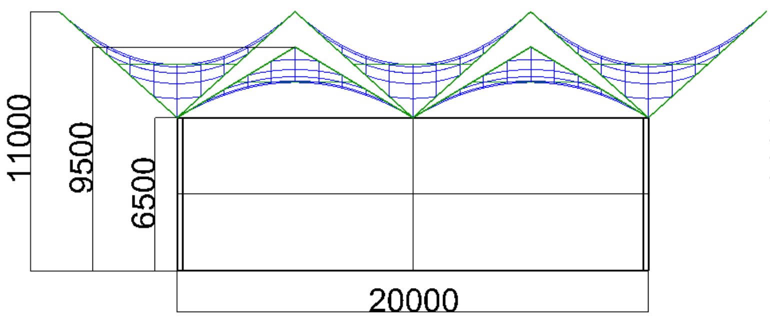


Figure 10.1b: Schematic longitudinal Section

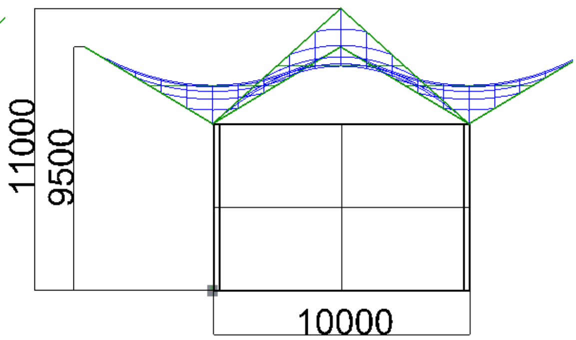
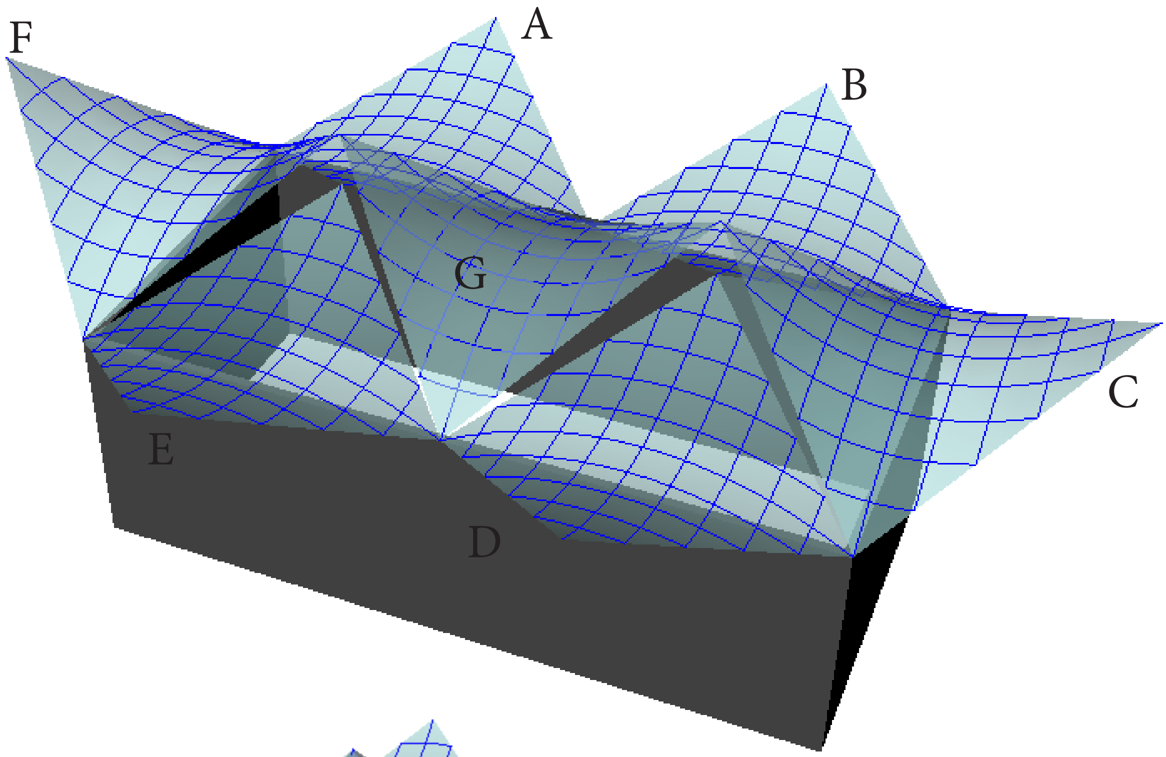


Figure 10.1c: Schematic Section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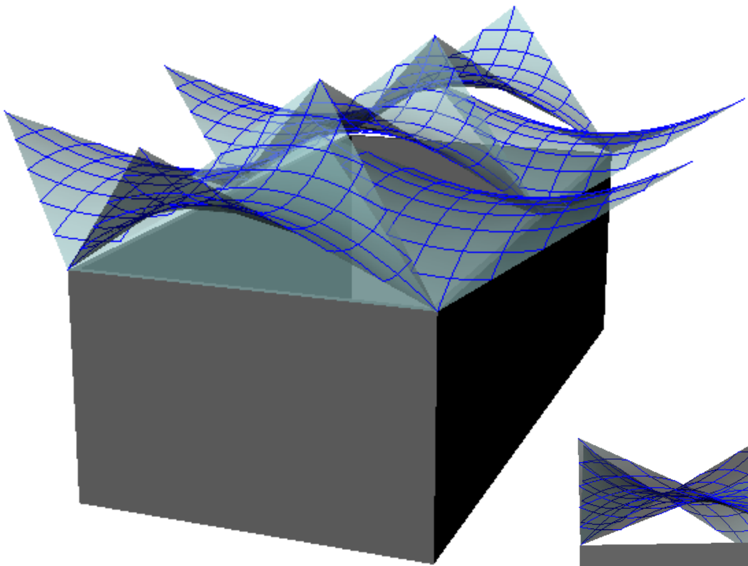
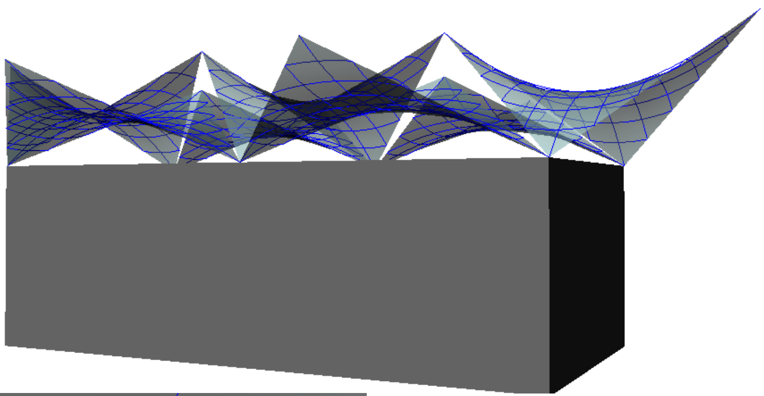
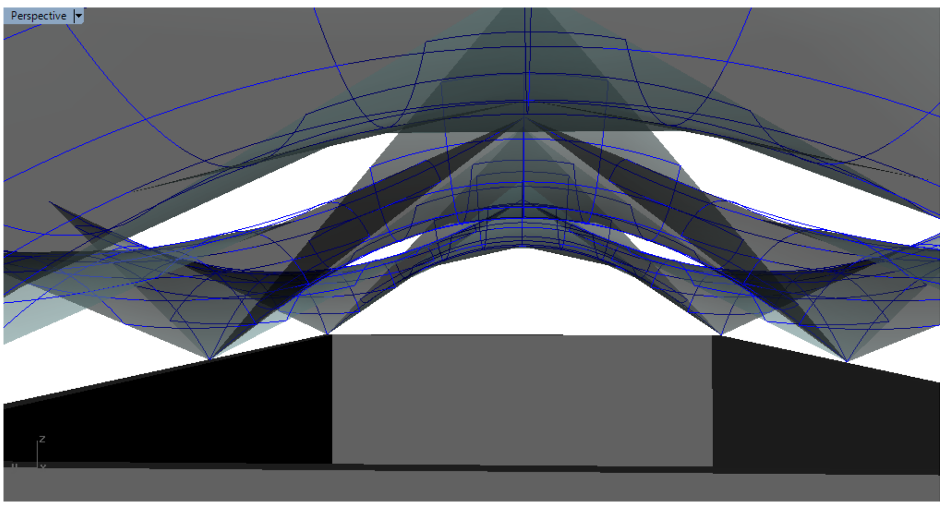





Perspective

BENDING ANALYSIS OF BAMBOO

11

11.1 EXPERIMENT GOAL

As pre-bent bamboo poles are used for the gridshell roof, the bending feasibility needs to be analyzed. The main criteria for bending bamboo is maximum curvature it can bend before yielding or failing and the extent it spring backs to its original position. After bending the bamboo it does not completely deform plastically. The maximum curvature depends on moisture content and size of the bamboo. While spring back deflection is dependent on moisture content, time period it is fixed in curved position and size of the bamboo. Hence bamboo needs to be processed before bending as explained in section 6.1.

As seen in the warehouse roof design, the gridshell is composed of two different hypar shells with different inclination. This difference in inclination generates parabolic arches of different curvatures. The blue gridshell (figure 11.1a) has a steeper inclination than the red. Thus small radius of curvature. Figure 11.1b indicates the curvature the bamboo should be bent.

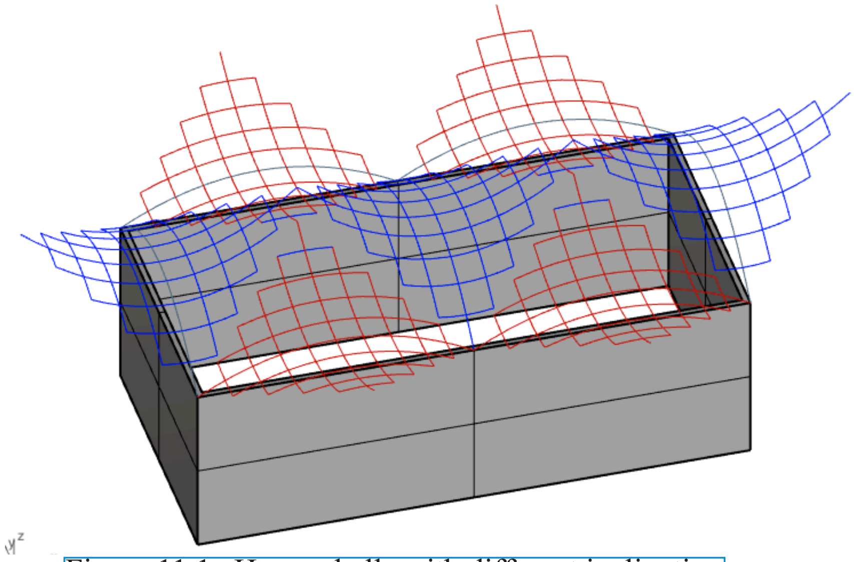


Figure 11.1a Hypar shells with different inclination

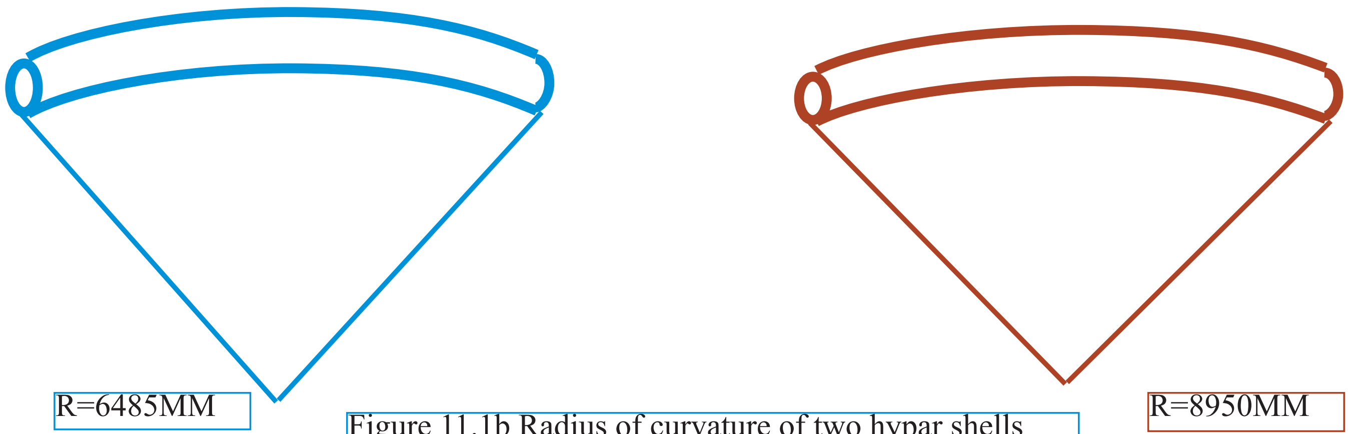


Figure 11.1b Radius of curvature of two hypar shells

11.2 MAXIMUM CURVATURE

When a material is curved, stresses are induced in it. After bending the members are fixed in the same position for some time. This is called the relaxation period. During relaxtion the stresses diminish. After relaxation the residual stresses which remain are less than the full stress induced in the production process. For wood, the residual stresses are approximately half of the initial stress level (Toussiant, 2007). The stresses formed depend on many material properties like moment of inertia, young's modulus and bending strength. If the maximum bending stresses formed exceed the ultimate stress limit of the material then it will lead to fatigue in the material. This will ultimately cause structure failure. The stresses in a curved beam are non-linear (Blass, 1995).

If the bending stiffness of the beam is more, then the bending radius of the beam will be less. Hence a bamboo which is stronger will curve further prior to failure than a weak bamboo pole. A larger bending stiffness also means larger modulus of elasticity. A larger moment or force is required to bend a strong section of beam to the same radius compared to a weaker one.

According to Navier's theory of elasticity, in a curved beam the strain on the outer layer of the section is less than the strain in the inner layer. In order to regain equilibrium of forces the neutral line has to shift down (figure 11.2a). As per Hooke's law the maximum bending stress in the outer layers (σ_o) is smaller than the maximum bending stress in the inner layers (σ_i) (Blass, 1995).

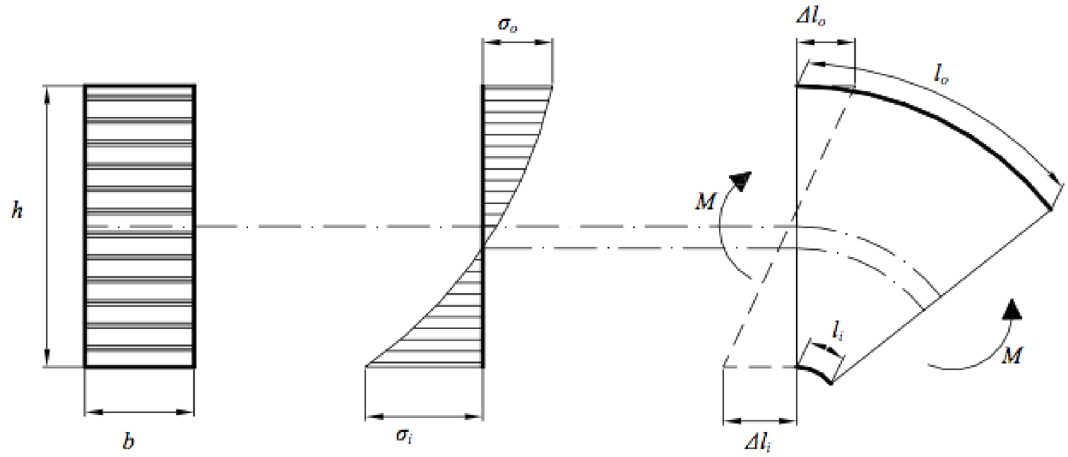


Figure 11.2a: Distribution of stresses in a curved beam (Blass, 1995)

MATERIAL AND METHOD FOR TESTING

Two kind of bamboo specimens were tested using 3-point bending test. The materials were obtained from Bamboe Bouw Nederlands. Initially tests were conducted using specimens with smaller diameter and length. Limited number of tests were done due to lack of time and resources. However in depth study is required for studying both the factors of bamboo i.e maximum curvature and spring back deflection.

Test 1

In order to find the maximum radius, the maximum mid-span deflection before yielding was obtained from 3-point bending test. Different specimens were used with diameter ranging from 1.5cm - 2cm. The length of the specimen was around 29cm - 31cm. Specimens with nodes in the center, nodes in the end and no nodes were selected to check the influences of nodes on bending. The specimens were also categorized as per processing or treatment done before bending. Few specimens were soaked in water for 12 hours before testing, heated using a heat gun for 5 minutes and remaining were tested without any treatment.

Specimens

Without treatment.
1a) No nodes
1b) Nodes in the end
1c) Nodes in the center.

Soaked in water for 12 hours.
2a) No nodes
2b) Nodes in the end
2c) Nodes in the center

Heating using a heat gun.
3a) No nodes
3b) Nodes in the end
3c) Nodes in the center

The specimens were loaded till it completely failed. A graph was obtained from the tests, showing load, deformation curvature of the specimens. The bamboo behaves linearly elastic initially then reaches a peak stress point and subsequent failure (figure 11.2f). At the point of peak stress, initial cracks propagates. Between this stage and complete failure, the strength of the bamboo is still significant. As only one test was conducted on one type of specimen, the influence of nodes and treatment cannot be concluded. Hence a number of tests needs to be conducted.

From this test it can be determined the curvature obtained is more than the curvature required. The average maximum radius that can be obtained from 2cm diameter is 1.1m, and the required radius of the design is 6.4m and 8.9m. That means if 2cm diameter of bamboo is used for this design then it can bend to that limit.

The moisture content of the specimens were not determined and is recommended to evaluate the specimens based on it. Also as mentioned before the influence of nodal positions were not determined and hence a number of tests needs to be conducted using same kind of specimens and treatment.

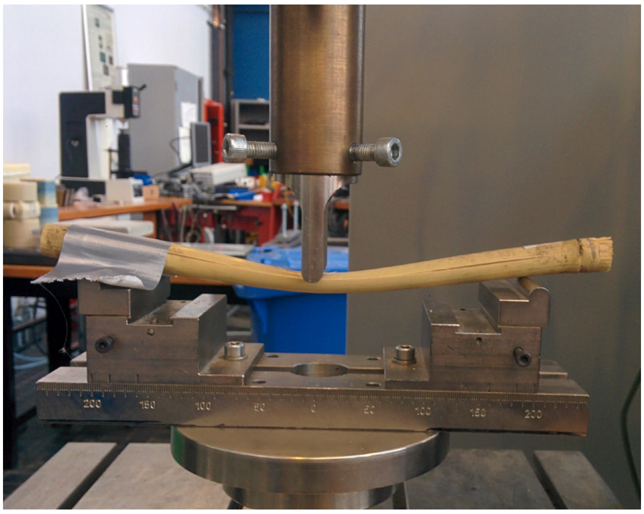


Figure 11.2e: 3-point bending test.

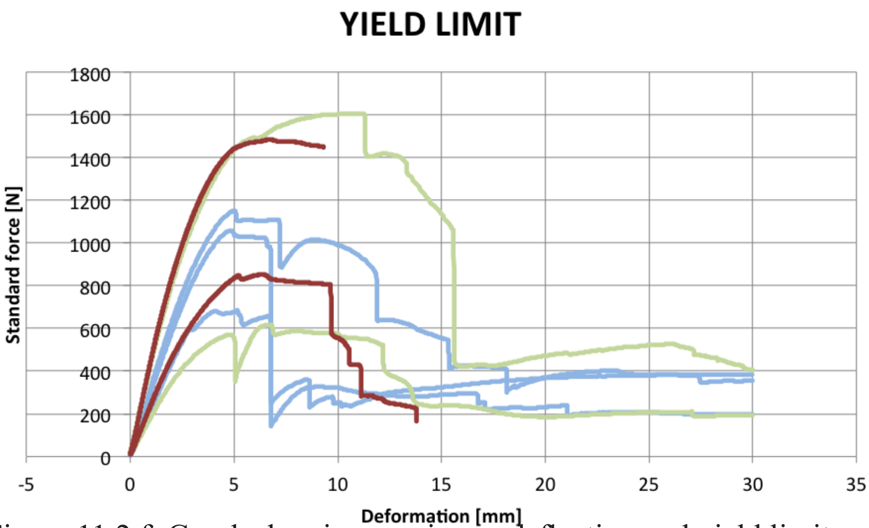


Figure 11.2 f: Graph showing maximum deflection and yield limit.

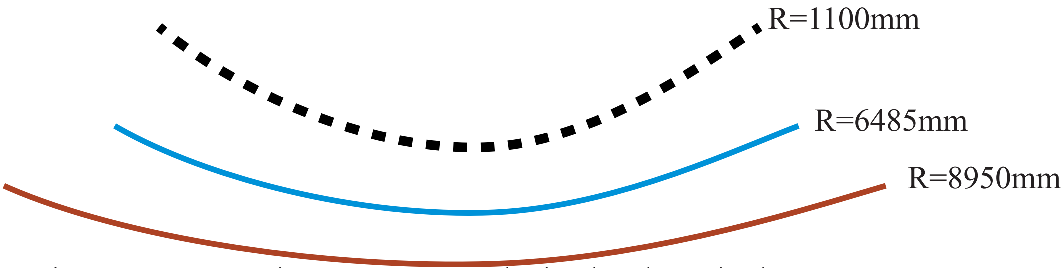


Figure 11.2 g: maximum curvature obtained and required

	Length mm	Dout mm	Din mm	Thickness mm	F_{max} N	dL at F_{max} mm	I mm^4
Specimen 1a	192	17	12	5	1617.0985	7.61122	3080.38906
Specimen 2a	186	17	13	4	617.21252	6.812631	2696.475
Specimen 3a	188	16.5	12.5	4	1607.1478	10.68952	2438.70063
Specimen 1b	168	17	13	4	1373.7449	7.80918	2696.475
Specimen 2b	260	16.5	12.5	4	1151.0383	5.040975	2438.70063
Specimen 3b	220	17	13	4	683.81958	5.197515	2696.475
Specimen 1c	200	16.5	12.5	4	2858.7397	9.831169	2438.70063
Specimen 2c	191	17	13	4	1485.7621	6.829357	2696.475
Specimen 3c	225	15.5	11.5	4	851.97394	6.26263	1973.78438

Figure 11.2 h: maximum deflections and critical force from 3-point bending tests.

With the 3-point bending test, properties of bamboo can only be determined in transverse direction. But bamboo is a functionally graded fibre reinforced composite. It is anisotropic in nature. The bamboo properties were used for FEA by (Khatry & Mishra, 2012) . The properties were determined in all three directions and also the culm wall was split into three and each layer was assigned different properties. This was done because of the non homogeneous nature of bamboo.
Using the properties from this literature and boundary conditions of 3-point bending test, FEA was performed Ansys workbench. Bamboo of length 300mm and 4mm wall thickness split into 3 functionally graded layers was modeled (figure 11.2h). Central point load with two fixing points were assigned. The bamboo was fixed at half the circumference and offset from the ends as per the tests. The section layers of bamboo were modeled as a composite. The deflections found with finite element were similar to the deflection in the tests results (figure 11.2i and figure 11.2g). This suggests that these properties can be used for further structural calculations of the bamboo roof.

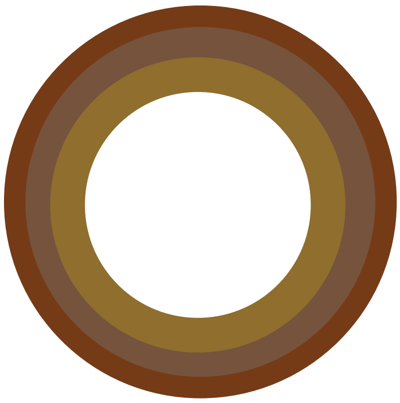


Figure 11.2h: Bamboo culm wall divided into three layers for FE analysis.

Property	Outer layer	Middle layer	Inner layer	Nodal element	Steel	Unit
Density	710	710	710	710	7850	kg/m^3
Orthotropic Elasticity						
Young's Modulus X direction	1.7E+10	1.6E+10	1.2E+10	1.7E+10	2.00E+11	Pa
Young's Modulus Y direction	6.2E+08	4.7E+08	3.4E+08	1.7E+10	2.00E+11	Pa
Young's Modulus Z direction	6.2E+08	4.7E+08	3.4E+08	1.7E+10	2.00E+11	Pa
Poisson's Ratio XY	0.3	0.3	0.3	0.3	0.3	
Poisson's Ratio YZ	0.3	0.3	0.3	0.3	0.3	
Poisson's Ratio XZ	0.3	0.3	0.3	0.3	0.3	
Shear Modulus XY	3.1E+08	2.3E+08	1.7E+08	2.3E+08	7.69E+10	Pa
Shear Modulus YZ	8.5E+09	8E+09	6E+09	8E+09	7.69E+10	Pa
Shear Modulus XZ	3.1E+08	2.3E+08	1.7E+08	2.3E+08	7.69E+10	Pa
Tensile Ultimate Strength	2.2E+08	2E+08	1.6E+08	1.06E+08	7.69E+10	Pa
Compressive Ultimate Strength	9.20E+07	8.00E+07	6.40E+07	8.00E+07	N/A	Pa

Figure 11.2i: Orthotropic bamboo properties distributed in three layers.
ref: (Khatry & Mishra, 2012)

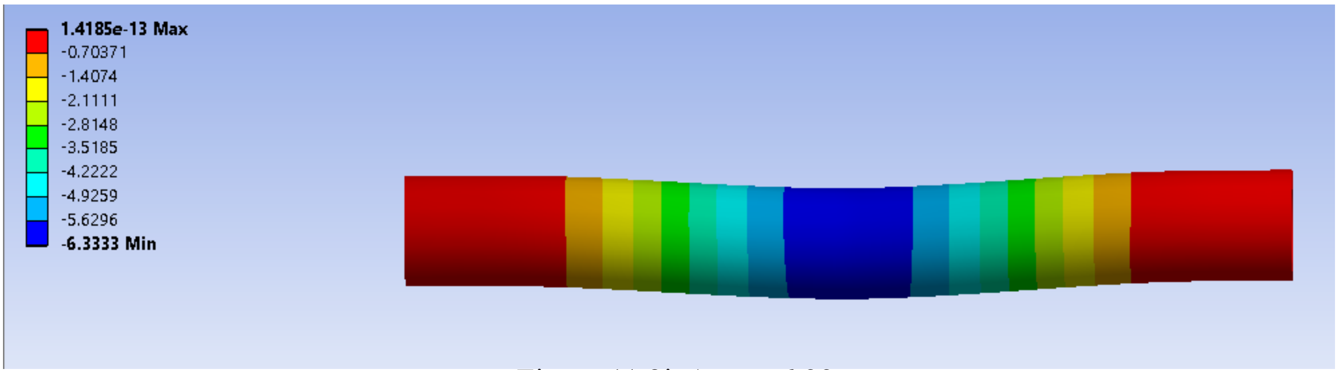


Figure 11.2j: Δ_{zmax} = 6.33mm

11.3 SPRING BACK DEFLECTION

Test 2

This test was done to determine spring back deflection of bamboo. The specimens used were same as the previous test. As the spring back deflection will be the final curvature of the bamboo for construction. This will determine the kind of joinery and tolerances that needs to be accounted.

Bamboo once unloaded will deform back to some extent. More the duration of load, less will be the spring back. In practice the deformed bamboo is kept in curvature for 3-4 hours till the bamboo is dried. Before bending, it is processed using the steaming method (section 6.1). But due to limitations in the laboratory, the bamboo was processes by soaking in water for 6 days. The time duration for loading was also less. The specimens were loaded for 15mins, 30mins and 45mins. Hence the spring back deflection that occurred during experiments were more than that generally occurs during practice or construction.

Again the experiment was performed using 3-point bending test. The deflection was kept constant and the force varied with time. So the force keeps increasing till the specimen reaches that constant deflection. Once it is deflected the force reduces with the time set. For a specimen length of 270mm, a deflection of 2mm and 0.6mm is required as per the roof design (figure 11.3a and figure 11.1a). A constant deflection of 5mm was given. This was predicted as in the Test 1 the bamboo specimens yielded at around 6mm - 7mm. And the specimens need to deflect without yielding. So if 5mm deflection was given as input parameter, and if loaded for 45mins it deflected back 72% (figure 11.3c). The final deflection was 1.4mm. This spring back deflection is quite high because of less loading period. In general practice a spring back deflection of 50% or less is usually experienced.

After unloading, the specimen was allowed to deform back. The spring back deflection was checked by moving actuator till it touched the final deflected specimen. The difference between the final deflection and the original deflection is the change in deflection obtained.

	Length mm	Dout mm	Thickness mm	Constant dL mm	Time mins	F_{max} N	Ffinal N	Final dL mm	Springback %
Specimen 1	305	19.5	4	5	30	758.05	490.77	1.16	76.8
Specimen 2	320	18.5	3	7	30	566	348.63	1.53	78.14
Specimen 3	300	18	4	5	15	1034	727.03	0.95	81
Specimen 4	295	18.5	5	5	45	1063	665.11	1.4	72

Figure 11.3c: Test results for spring back deflection.

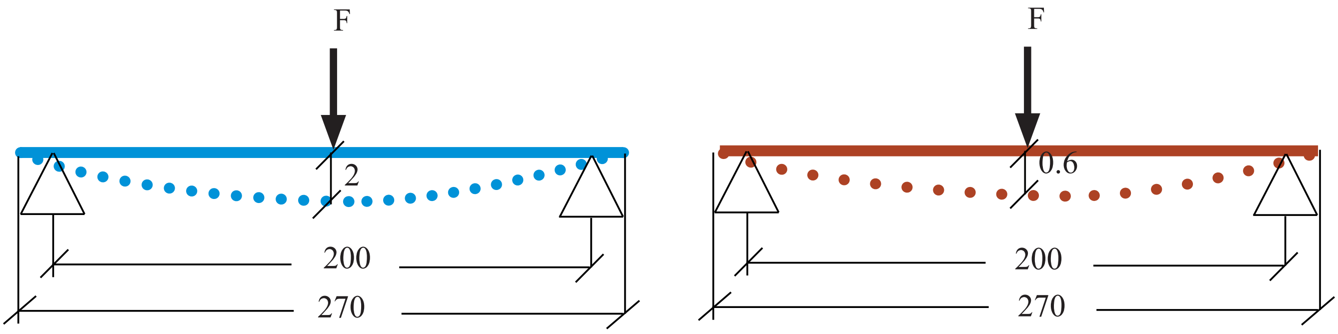


Figure 11.3a Deflection required as per design.

As the length of the specimen was too short, it is bent to very little extent. The outer fibers of the specimen were deformed instead of the entire specimen deflecting. Hence the results obtained for bending were not completely accurate. Also the specimens failed not because of bending stresses but because of shear splitting (Gottron, 2013).
For flexural tests, if specimen length of 30D or greater is selected the it will fail because of bending (Gottron, 2013). Hence the next set of experiments were performed using longer lenth specimens.

Test 3

Specimens of longer length were selected to determine the spring back deflection. For bamboo length 920mm, deflection of 16mm and 12mm is required according to the roof design. The specimens were soaked in water for 9 days. Longer specimens yielded at a deflection above 60mm (figure 11.3d). Hence a constant deflection of 60mm was given. The loading period was 30 minutes. The specimen deflected 73.9%. The required final deflection of 16mm was achieved. The final deflection was 15.6mm (figure 11.3e).

This test was comparatively accurate than test 2 as the entire bamboo specimen deflected instead of denting the upper surface (figure 11.3g). Compared to shorter specimens, the longer specimens yielded at a lower force (figure 11.2f and figure 11.3d). This may be because the splitting of bamboo occurred due to bending stresses. Whereas in shorter bamboo, failure was because of shear stresses.

Figure 11.3d: Yield limit of bamboo 920mm and diameter 20mm

	Length mm	Dout mm	Thickness mm	Constant dl mm	Time mins	F_{max} N	Ffinal N	Final dL mm	Springback %
Specimen 1	305	16	4	60	30	464.76	341.86	15.61	73.9

Figure 11.3e: Test results for spring back deflection.

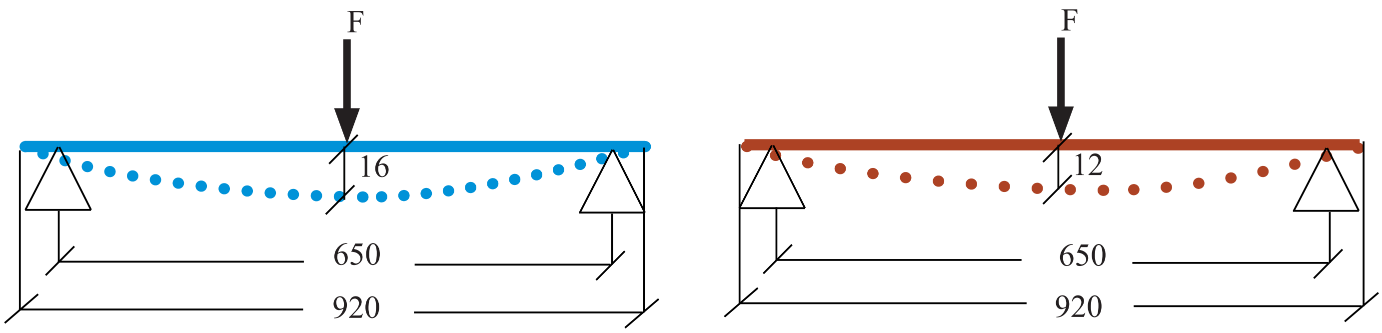


Figure 11.3f: Deflection required as per design.

Figure 11.3g: 3-point bending test with longer specimen

Test 4

Specimens of smaller diameter - 20mm, were able to bend or curve as per the design curvature. But for construction bamboo of diameter above 30mm is generally used, because of required stiffness. Hence bamboo of diameter 50mm and same length around 900mm-920mm were used for this experiment.

The yield deflection of the specimens range from 9mm - 11.76mm (figure 11.3i). Hence the maximum curvature obtained is less than the curvature required for the design (figure 11.3j). As the specimens were soaked in water the moisture content was not enough the bend a stiff bamboo.

In order to check the spring back deflection, specimens were subjected to constant load of 10mm for 30 minutes and 45 minutes. For 45 minutes, the spring back was 49% with final deflection 5.08mm (figure 11.3i). But the required deflection for 900mm length of bamboo is 16mm and 12mm (figure 11.3f). Hence some alteration in the experiments and design is required and is discussed in the next chapter.

Figure 11.3h: 3-point bending test of bamboo length 920mm and diameter 50mm.

	Length mm	Dout mm	Thickness mm	Constant dl mm	Time mins	F_{max} N	Ffinal N	Final dL mm	Springback %
Specimen 1	900	50	5	10	30	1134.72	773.28	2.24	73.9
Specimen 2	900	50	5	10	45	1159.8	702.26	5.089	49.11

Figure 11.3i: Test results for spring back deflection.

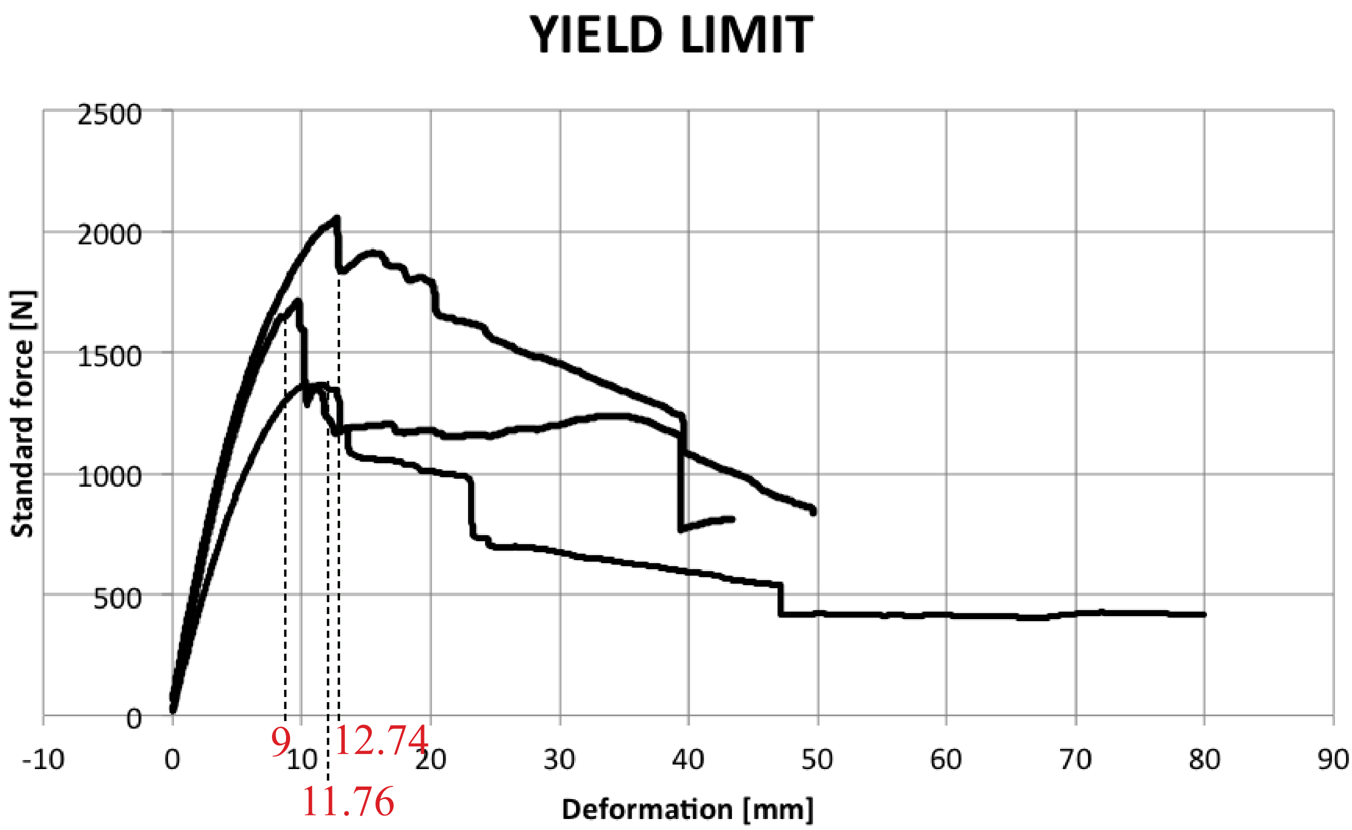


Figure 11.3i: yield limit of bamboo length 920mm and diameter 50mm.

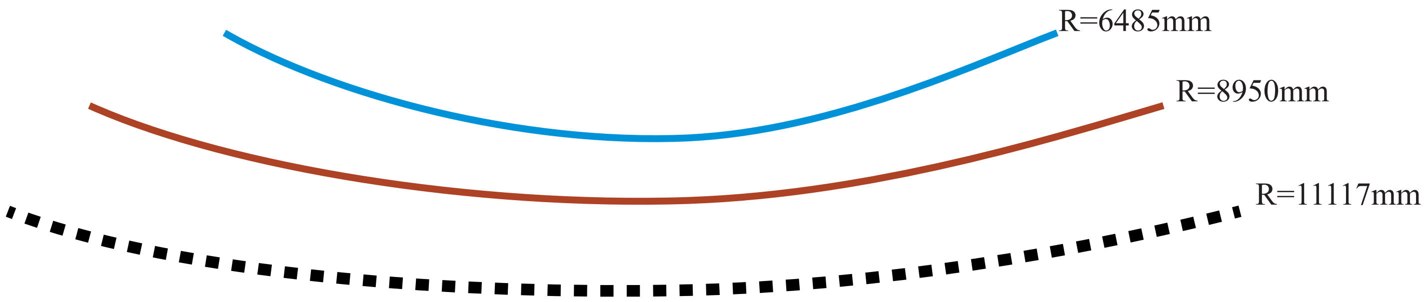


Figure 11.3j: Maximum curvature required and obtained of bamboo 50mm diameter.

11.4 BAMBOO BENDING EXPERIMENTS CONCLUSION

From the above experiments, it is clear that the ratio of length and diameter is important while testing the bamboo. If bamboo specimen of length less than 30D is selected, it is stiff to bend, rupturing the upper fibres. There will be a dent formed on the surface in contact with the actuator. This length was theoretically determined by Vaessen and Janssen (1997). Thus to develop flexural capacity span to depth ratio should be more than 10 (Gottron, 2013). Splitting is the most dominant failure observed in bamboo specimens.

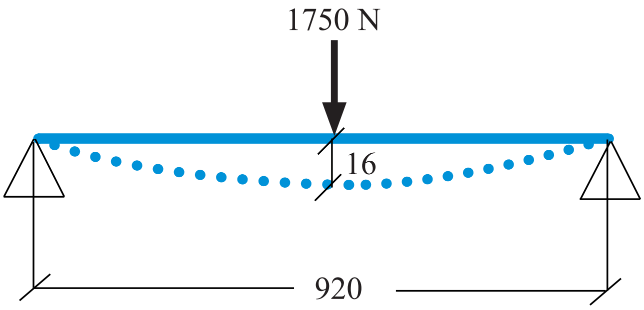
All the specimens were soaked in water but steaming is the most preferred treatment before bending bamboo. With steaming process, the fibres become soft, which makes bending easy without splitting. The colour of larger diameter bamboo specimens suggested they were over dry and also had some cracks on it. Hence the specimens started to split at a very low deflection.

FOUR POINT FLEXURAL TEST

As the deflections are small, linear beam theory is assumed for analytical study of the force and stress acting on the specimens. In a three point bending test, a single concentrated point load is used. The bending moment is zero at the ends and gradually increases to maximum at the center where its loaded. Greater the bending moment greater will be the stresses developed and will yield or in this case split easily. Instead of using a three point bending test, four point bending test should be performed to obtain a greater curvature. If a load of 1750N is considered (average critical force from test 4; figure 11.3i), then the stress developed is 95.42 MPa. The specimens underwent a deflection of around 11mm and according to calculations the deflection is 16mm. However maximum bending moment is lower when two point loads are subjected. This also means bending stresses in this case are lower than bending stresses developed in point load. For four point bending, two point loads with the total load of 2100N is considered. The maximum bending moment is constant between the two loads. With lower stresses generated the specimen will deflect same as three point bending.

STRESSES ACTING ON THE SPECIMEN

Although bamboo is good in resisting tensile force, but this is only in axial direction. When loaded perpendicular to the main axis, i.e. in transverse direction it is weak in tension than compression. It was observed that cracks propagate at the lower part of the specimens. When loaded in vertical downward direction, as in case of 3-point bending test, the upper fibers are in compression and lower fibres are in tension. Hence the specimen fail due to tensile bending stress (figure 11.4b). But this is only true for longer specimens, or specimens with length more than 30D. When shorter length specimens are tested, it fails due to shear stress (figure 11.4c) (Gottron, 2013).



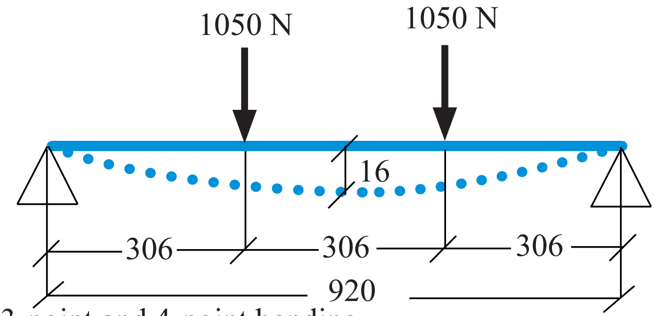
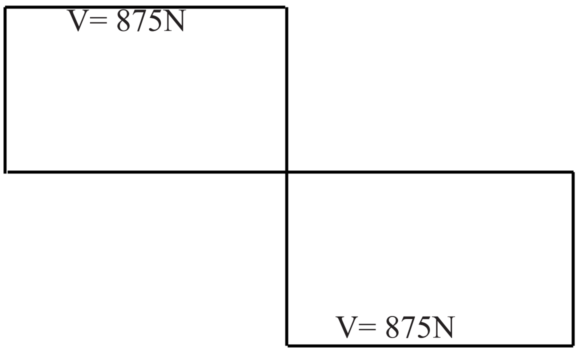


Figure 11.4a: Boundary condition for 3-point and 4-point bending



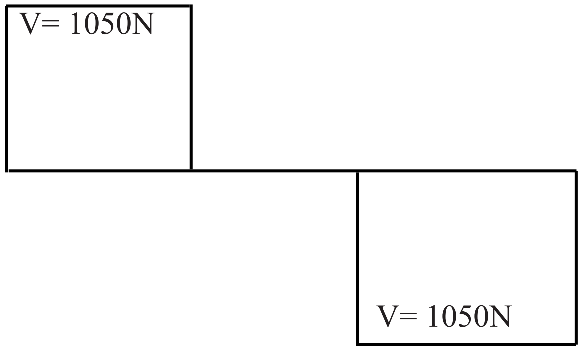
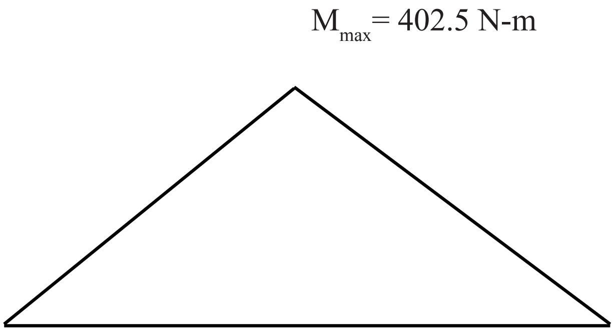


Figure 11.4a: Maximum shear force



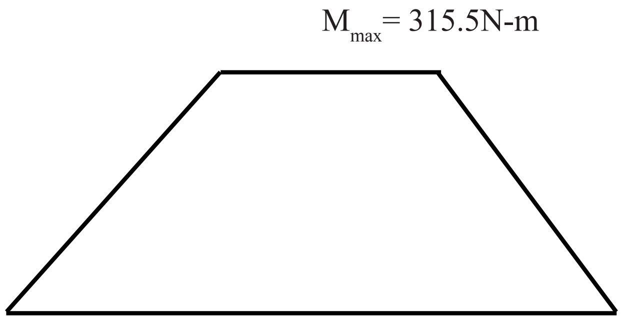


Figure 11.4a: Maximum bending moment

$$\text{Flexural Stress} = \frac{My}{I}$$

Flexural Stress = 95.42 MPa

Flexural Stress = 74.67 MPa

$$\text{Deflection } \Delta_{max} = \frac{Pl^3}{48EI}$$

$$\text{Deflection } \Delta_{max} = \frac{Pa\,(3l^2-4a^2)}{24EI}$$

Δ_z = - 17.87 MM

Δ_z = - 18.01 MM

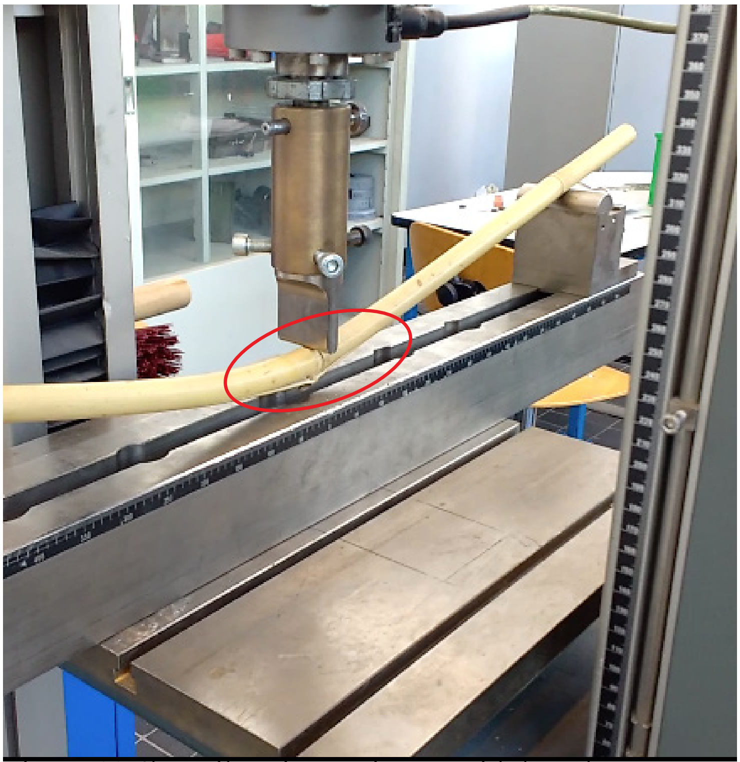


Figure 11.4b: Failure in specimens with length more than 30D.

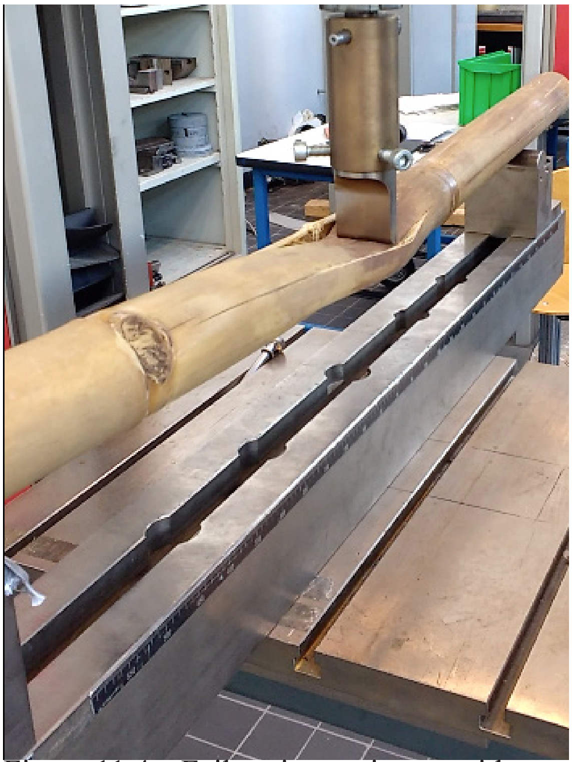


Figure 11.4c: Failure in specimens with length less than 26D.

Figure 11.4d: Bamboo steaming for bending.
ref: 24H Architect

Figure 11.4e: Bamboo bending using grid layout
ref: 24H Architect

SPRING BACK PREDICTION

From test 3 it shows that it is possible to determine what extent the specimen will spring back depending on the time it is loaded or time it is fixed in the curved position. Figure 11.4e shows how the bending of bamboo is done on site during construction. While testing the spring back deflection, the specimens were forced deformed by 3-point bending test. The first step was to know the yield strength of the specimen. Once the deflection limit was known, the bamboo was forced deformed for bending below this limit. The bamboo was deformed more than the required curvature because it undergoes a spring back once the loading is removed. Hence tests were performed till what extent it spring backs and how does time influence the final deflection. The curvature required for the roof design was also determined. After loading and unloading the bamboo the extent of spring back was known which was dependent mainly on time. In this case around 70% spring back was experienced if loaded for 30-45 minutes. Hence in test 3, the specimen was given a constant deflection of 70% more than required. And after the load is removed it was deflected back to the required curvature based on the roof hypar shell design.

It can be concluded that depending on the time of loading one can predict the spring back deflection. Now the next challenge is how to incorporate this spring back deflection method with the current technique used on site. The current technique of curving the bamboo on grid is quite adaptable. Before bending few tests should be performed (preferably a four point bending test) on same kind of specimens which are going to be used for construction. Once the percentage of spring back deflection is known, the bamboo should be bent to that extra amount (figure 11.4f). If the testing of bamboo is not possible then it can be deformed using the grid system and check the spring back deflection. Based on the results the grid can adjust accordingly.

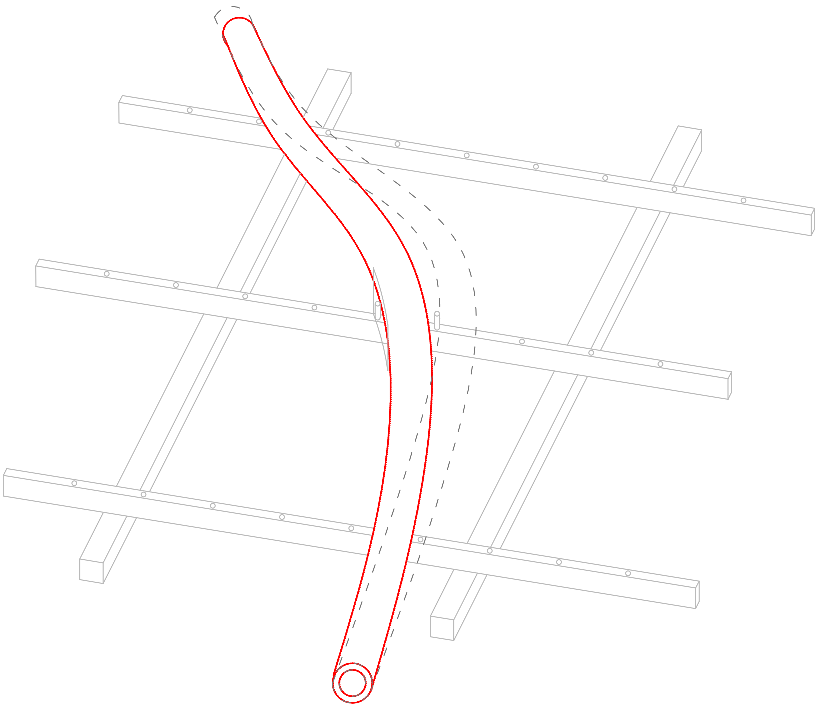


Figure 11.4f: Extra bending of bamboo using grid layout to account for spring back

SHELL OPTIMIZATION

Test 4 results show that, bamboo of diameter 50mm did not bend or curve according to the curvature in the design (figure 11.3j). Even if bamboo was treated with steaming process before bending, it might not curve to the required extent because of high stiffness. Hence the form of the gridshell roof is optimized. The blue hypar shell structure has a greater curvature, that means smaller radius compared to red hypar shell (figure 11.4g and figure11.4i). So the curvature of blue shell structure is altered. The inclination i.e. ratio of span to height of the shell is reduced, bringing it almost down till the red roof (figur11.4h and figure 11.4j). By doing this, the radius of the curved bamboo increases. The diameter of the bamboo should also be reduced from 5cm to 4cm, decreasing its stiffness.

Hence by optimizing the radius of curvature, changing the diameter and using 4-point flexural test, bending bamboo as per the roof design is possible.

11.4 BAMBOO BENDING EXPERIMENTS RECOMMENDATION

1. For pre-bent bamboo grid members, it should be processed using the steaming method before doing the bending tests.
2. The moisture content of bamboo specimens should be determined.
3. If higher radius of curvature is required, 4-point bending test should be conducted.
4. In order to have flexural capacity, length of the specimens should be greater than 30D (Vaessen and Janssen 1997).
5.Numerous specimens of the same kind should be tested and verified.
6. Influence of nodes in different positions might have an effect on bending behaviour and should be tested for the same.

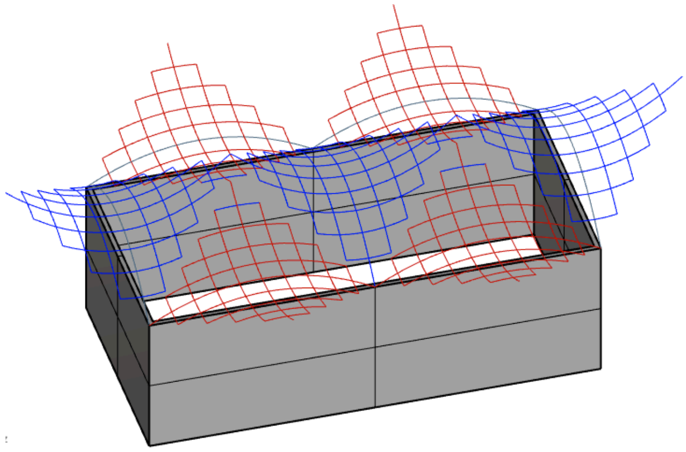


Figure 11.4g: Original gridshell design.

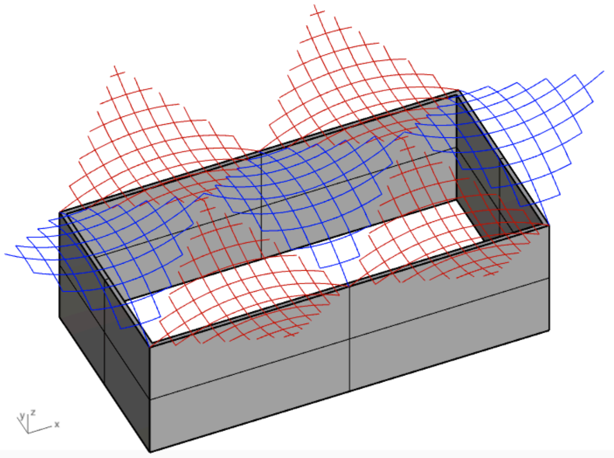


Figure 11.4h: Optimized shell, inclination of blue shell altered.

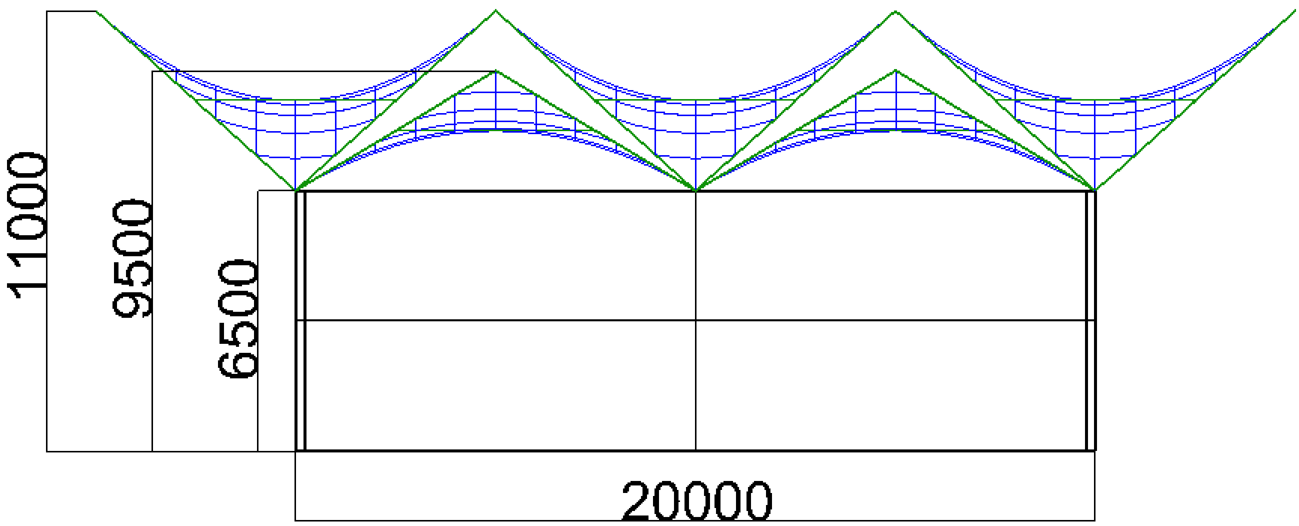


Figure 11.4i: Original section of gridshell design.

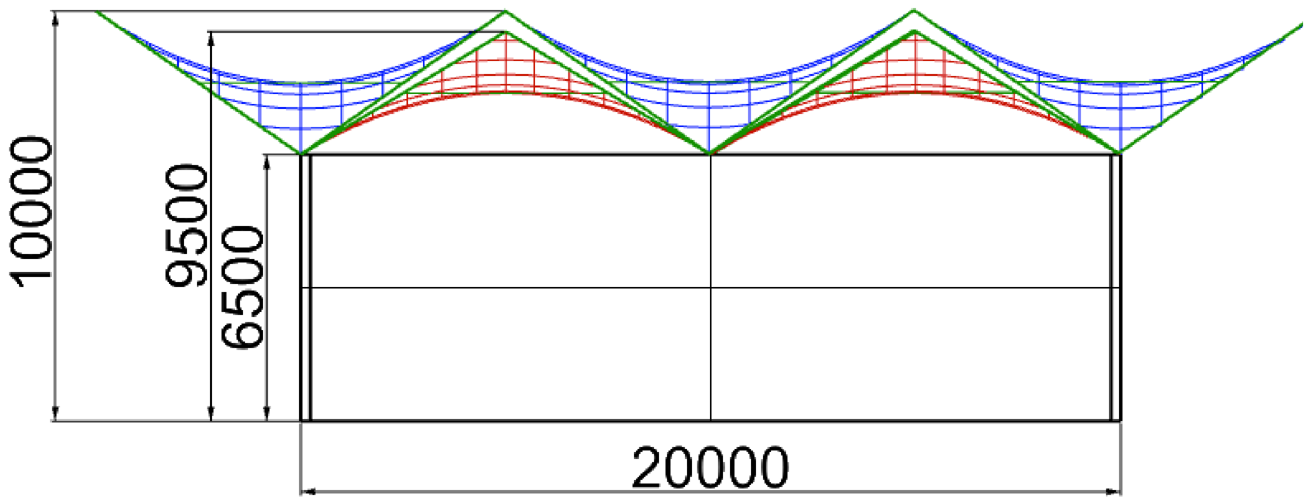


Figure 11.4j: Optimized shell section, inclination of blue shell altered.

THIN GLASS CLADDING SYSTEMS

12

Because of the complex shape of the roof structure, cladding material and method is carefully investigated. From conventional methods of using glass as a cladding material to innovative possibilities are discussed below. The most important factor was to protect the structure from rains, hence the cladding needs to be water tight.

12.1 FLAT PANELS - TESSELLATION

Tessellation is a very old technique of constructing a curved surface using 2-d planar elements. Triangulated planes approximate the curved surface. More the curved surface is segmented into triangles, smoother will the curvature.

MyZeil is a shopping mall in Frankfurt, Germany designed by Studio Fuksas in 2009. The envelope of this structure is fluid and conceived as a river. Because of different curvatures, glass was used in form of tessellation. The triangular panels are clamped on all three sides. That means the grid for this facade is triangular and not quadrangular.

The hypar roof shell structure designed for research has a quadrangular grid. Hence if tessellation method is to be used, extra diagonal members are required. This will introduce more number of joints and increase complexity. The number of glass panels would also increase. To create a water tight system will be difficult in this case. Either the joints between the two panels should be water-tight or the panels should overlap each other, forming a cascade. Overlapping becomes a challenge because all three sides of the panels should fall above or below each other. Hence this method of cladding was eliminated.

12.2 TWISTED PANELS

Each grid of the shell roof forms a double curved surface with negative gaussian curvature as discussed in section 7.1 (figure 12.2a). Negative gaussian curvature means the double curved surface is formed with two opposite curvatures. A flat panel can only be deformed to form developable surfaces. A piece of paper undergoes similar deformation. By bending the panel into developable surfaces, the panels are deformed without generating strains. Most of the developable surfaces have zero gaussian curvature that means it is curved on one axis and the other axis has zero curvature. So a flat panel can be deformed to a cylinder cone or a vault surface. But there is an exception. It can form a double curved surface by twisting or by applying torque to the panels. The radius of the curvature that can be obtained by twisting is large and limited. When panel is twisted further towards a larger deformation, a sharper diagonal deformations could appear (Eekhout & Staaks, 2009).

This was investigated in the project Zuidpoort which is a tram station in Delft, Netherlands. The design of the roof is undulated (figure 12.2c). Glass panels are cold warped (twisted) forming a continuous roof structure. The main structure that supports the glass frame is made up of steel frames. Glass is fixed by point supports. Glass panels of 1.5mx3.0mx100mm is used. Most of the glass panels used were rectangular but some panels were not orthogonal, in order to match the steel grid (Eekhout & Staaks, 2009).

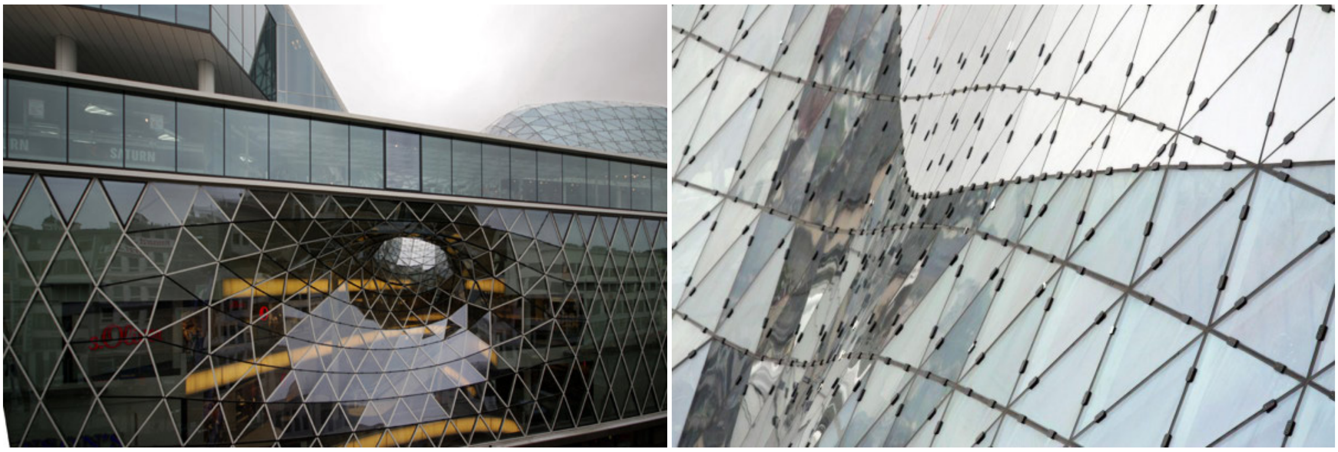


Figure 12.1a: My Zeil (Fuksas Studio)

- ✗ NO ADDITIONAL MEMBERS
- ✗ CLAMPING IN ONE DIRECTION
- ✗ OVERLAP REQUIRED IN ONE OR TWO DIRECTION

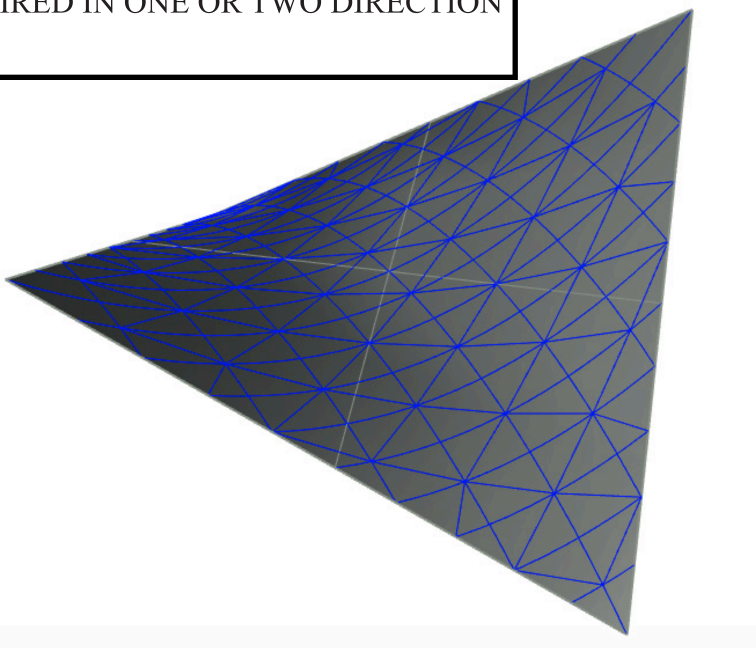


Figure 12.1b: Hypar shell roof clad with tessellated panels

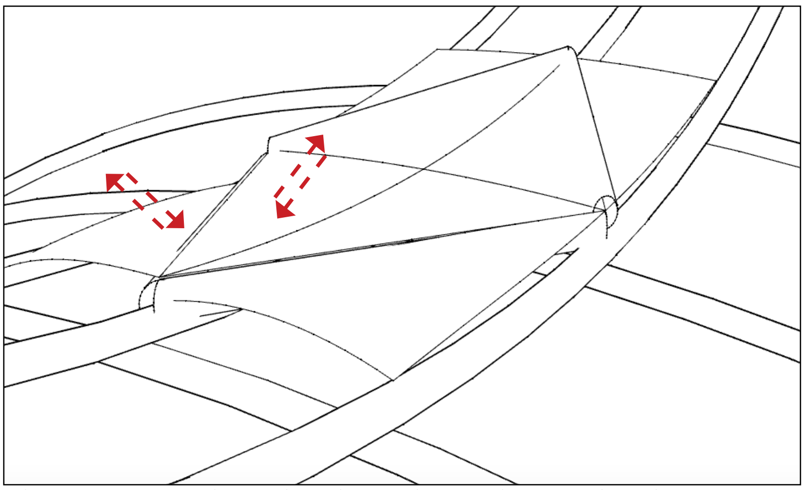


Figure 12.1c: Triangulated panels require overlapping

In the research design of bamboo and thin glass, by twisting the panels the edge points of the panel can be forced to converge with the grid nodes. In order to check the bending or twisting limit of thin glass, finite element analysis was done on Ansys workbench software. Double layer glass with two layers of PVB interlayer was modeled for FEA. The glass is fixed at point and remaining points are forced displaced vertically upwards or downwards (figure 12.2d). If the highest point on the grid is selected then all the points needs to be displaced downwards with varying magnitudes. This creates more stresses in the glass as the total displacement required is more. Hence glass should be fixed to nodes which are not the highest or th lowest nodal points (figure 12.2e). From the results it can be determined that glass can be twisted as per the required grid, without reaching its ultimate strength (200MPa)

Only the panel edge points will meet the nodes. Exact surface will not match the grid as by twisting the panel the sides remain straight, whereas the sides of the grid are curved. This creates a problem to make it water tight. As glass will be cold bent, to secure the panel in twisted form, clamping is required on all four sides. Also the twisted panel will exert a lot of pressure on bamboo. It will be difficult to control the flow of water from one panel to another because of the double curvature of the roof.

- ✓ NO ADDITIONAL MEMBERS
- ✗ CLAMPING IN ONE DIRECTION
- ✗ OVERLAP REQUIRED IN ONE OR TWO DIRECTION

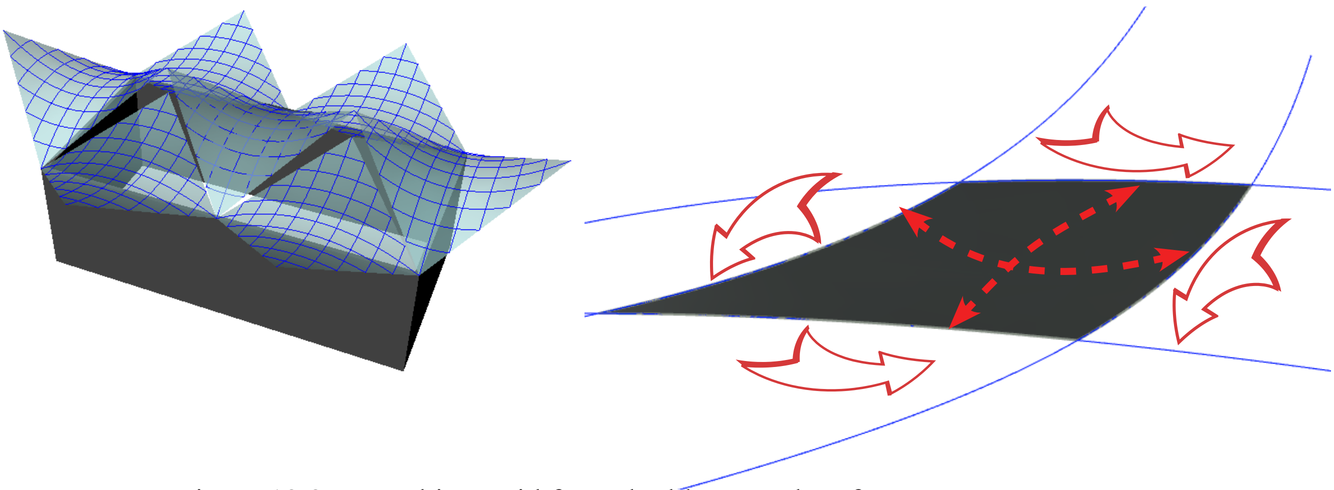


Figure 12.2a: Panel in a grid form double curved surface.

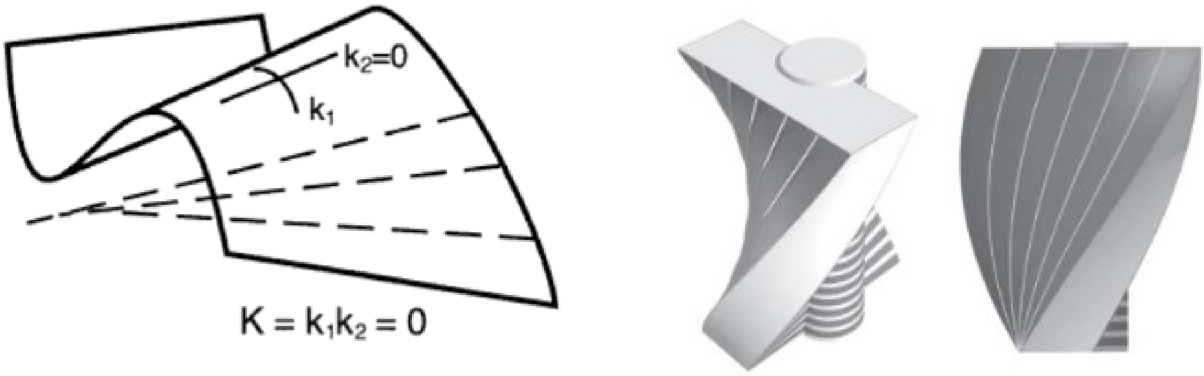


Figure 12.2b: Possibilities of deforming a flat panel without creating strains

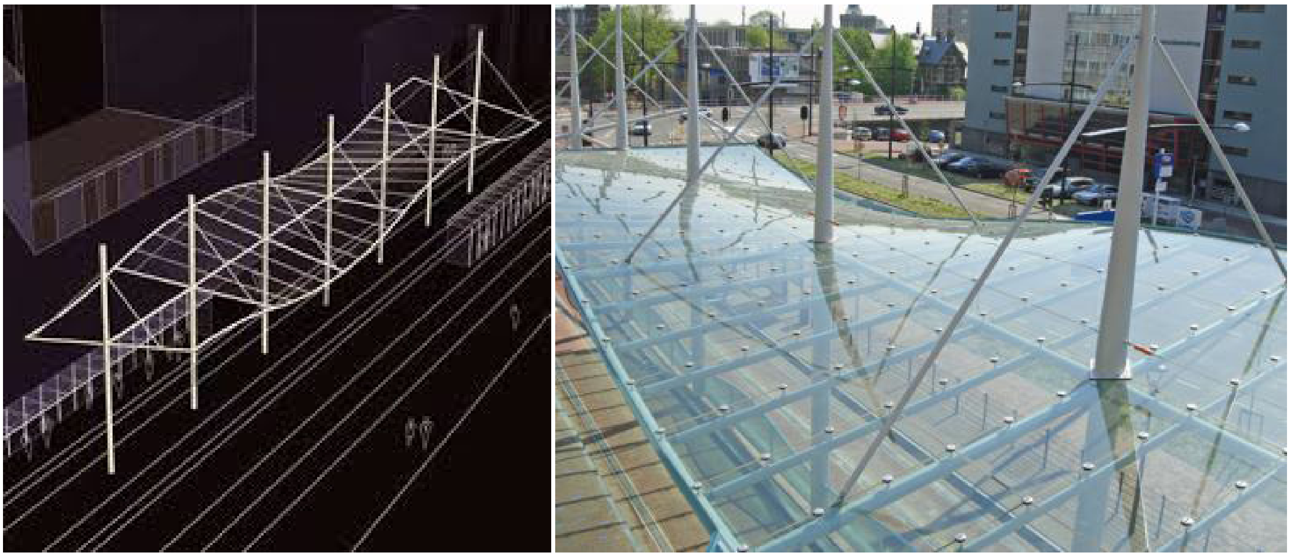


Figure 12.2c: Cold bent, double curved glass panels for zuidpoort roof - Octatube

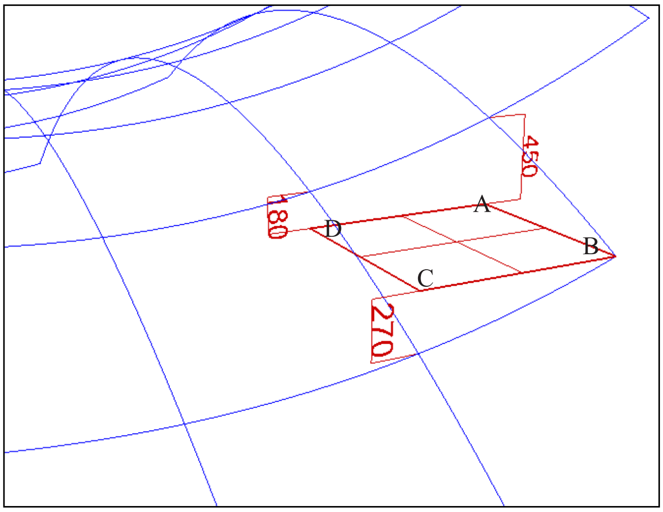


Figure 12.2d: Deflection needed at each point on the grid to twist the panel.

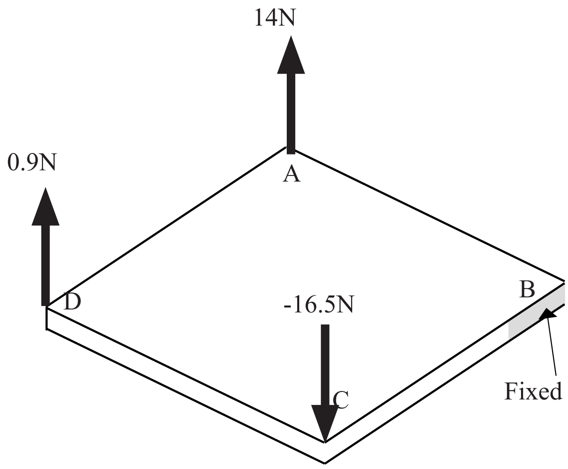


Figure 12.2e: Force required to deflect the panels to meet the grid nodes.

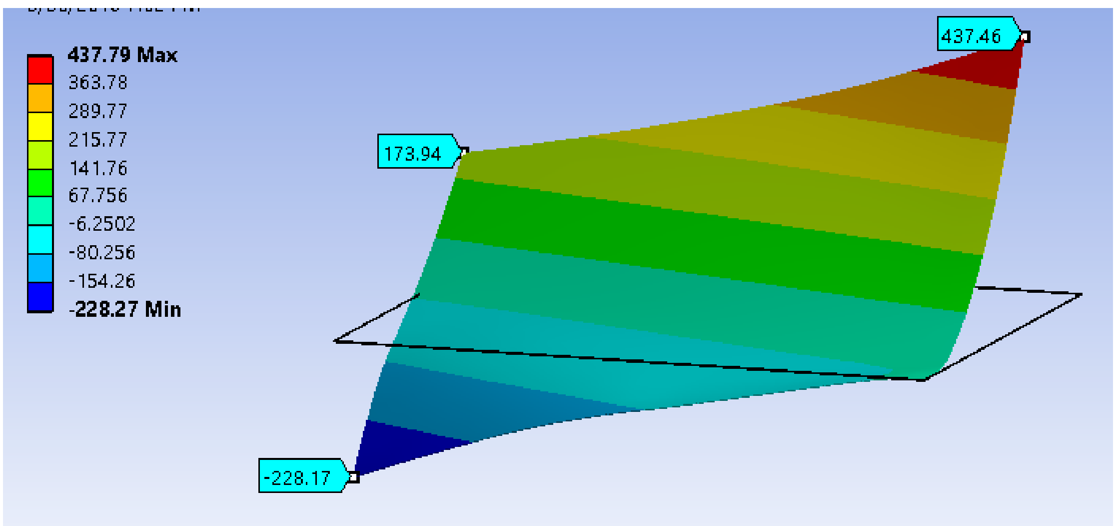


Figure 12.2f: Deflection Δa = Δc =   Δd =

12.3 SINGLE CURVE-CYLINDRICAL PANELS

In order to avoid clamping of glass on all four sides, it is cold bent into a cylindrical curvature. This way, the panel needs to be clamped only in one direction, on two parallel sides. In this case, the glass is clamped on the straight edges as it needs to be fixed to the bamboo skeletal structure below. Again with this method water-tightness needs to be solved.

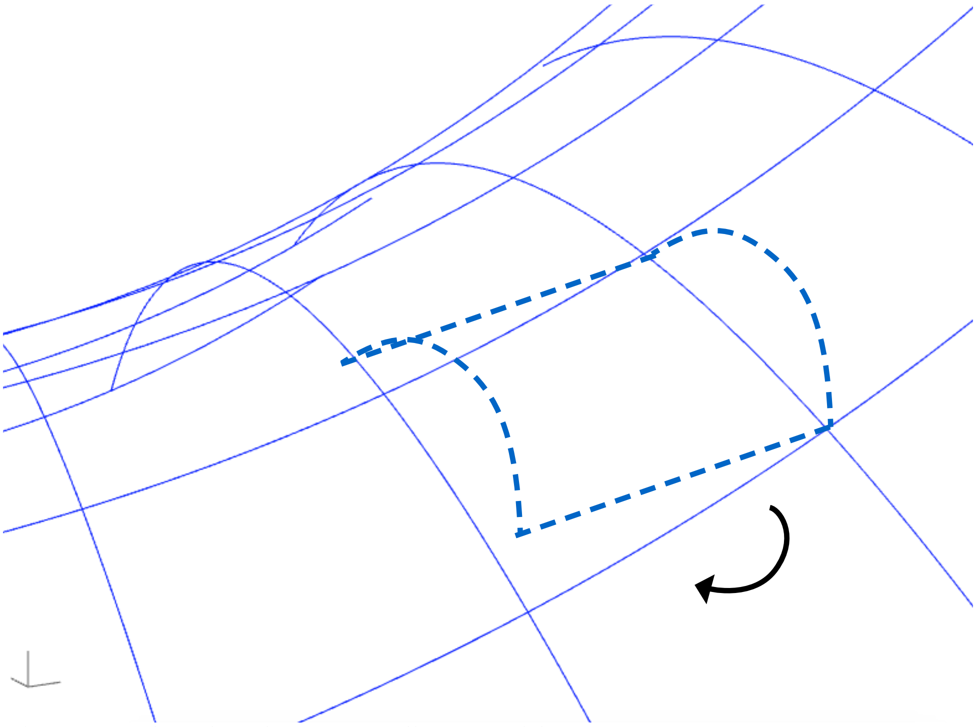


Figure 12.3b: Glass bent according to grid

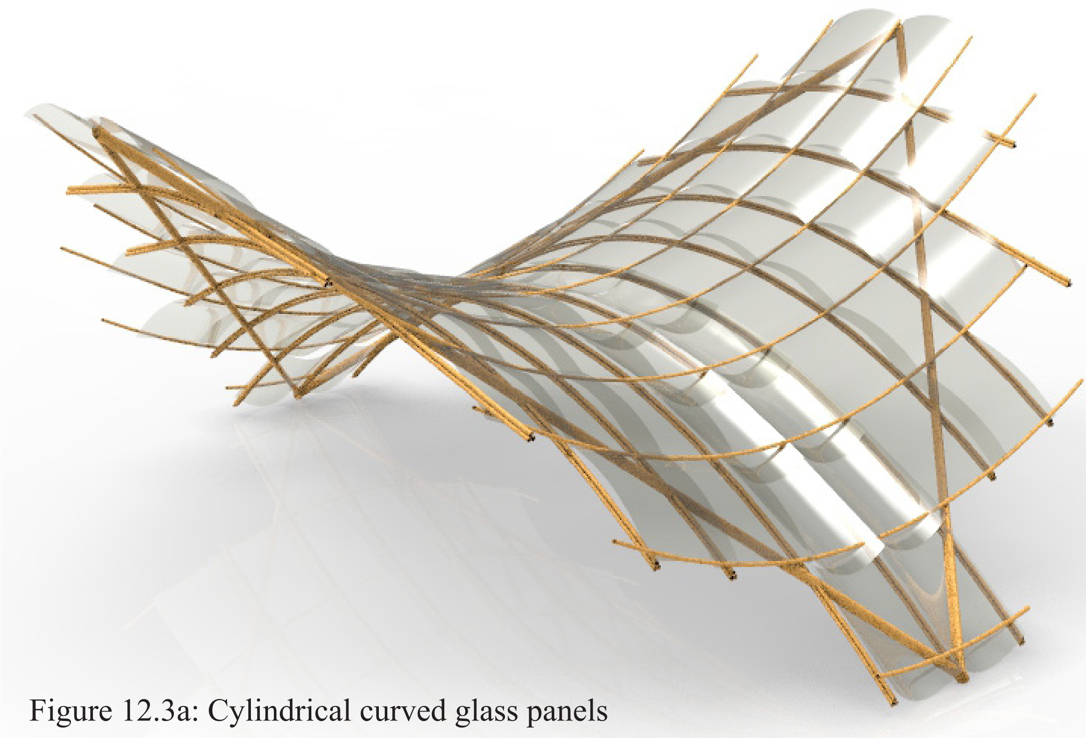


Figure 12.3a: Cylindrical curved glass panels

- ✓ NO ADDITIONAL MEMBERS
- ✓ CLAMPING IN ONE DIRECTION
- ✓ OVERLAP REQUIRED IN ONE OR TWO DIRECTION

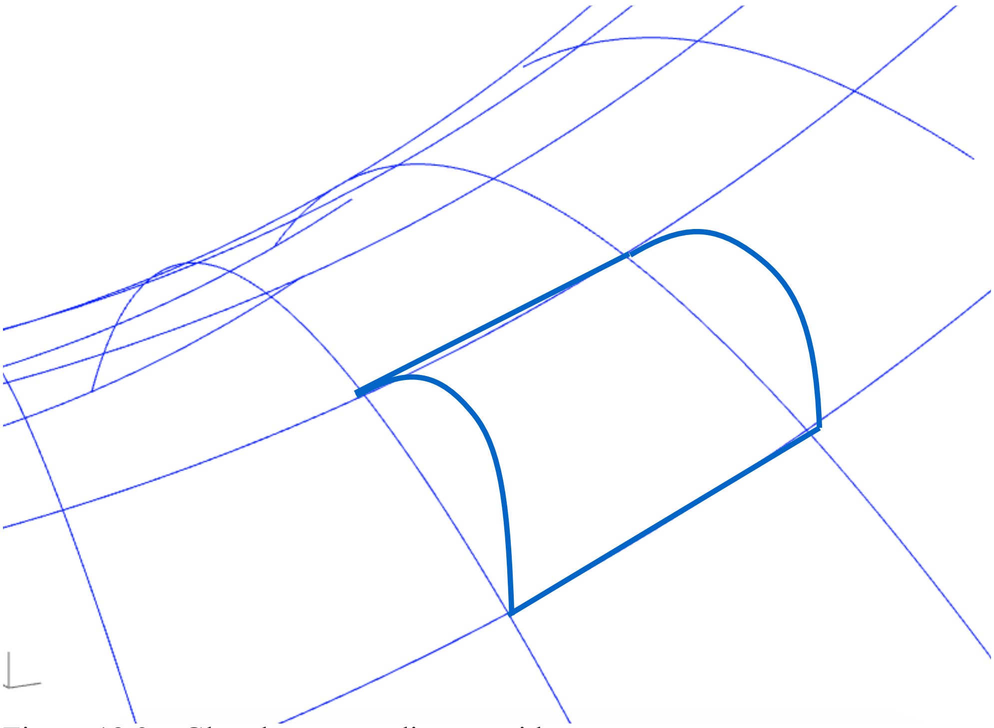


Figure 12.3c: Glass bent according to grid

12.4 PROBLEMS AND CHALLENGES

TOLERANCE

The structural roof is in the shape of hypar. The hypar shell is segmented to form parabolic curves. These segments are made up of bamboo canes. As bamboo is a natural material, it has no standardization. Apart from mechanical properties, even there are variations in physical properties. Tapering length, uneven diameter and nodal positions makes it challenging to develop a joinery system. Also the bending behaviour is not constant as discussed in section 11. When constructing with bamboo, the errors occurring on site are significant. When using other materials like steel or wood, errors occurring are small and in millimeters. But in case of bamboo, it reaches centimeters. Hence the tolerances because of bamboo construction are due to:

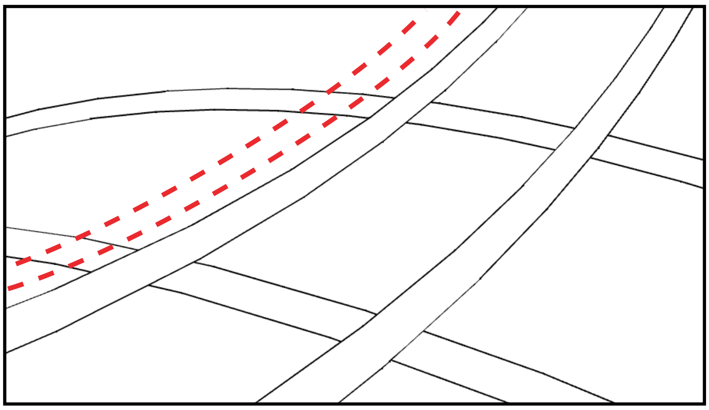


Figure 12.4a: Grid difference

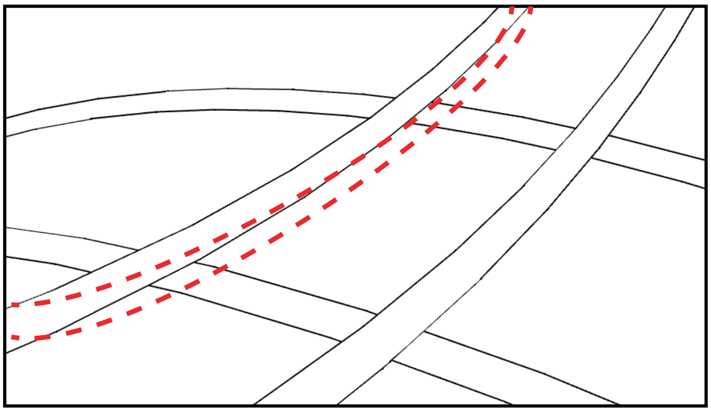


Figure 12.4b: In-plane bending difference

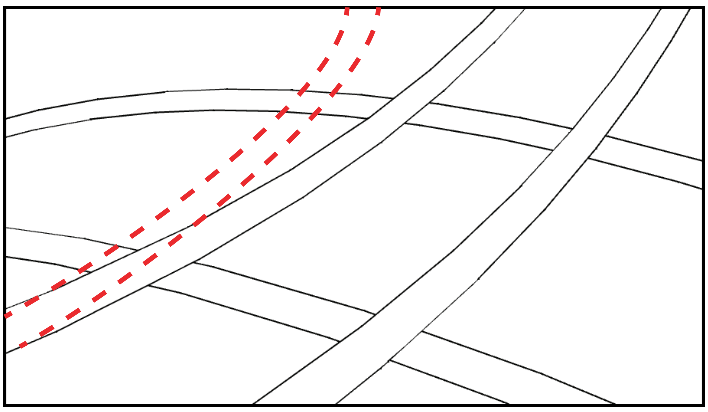


Figure 12.4c: Out-of-plane bending difference

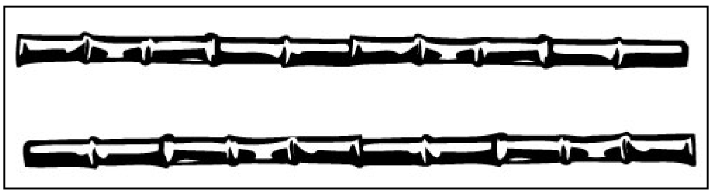


Figure 12.4d: Uneven diameter

CAN BE SOLVED BY

These tolerances can be solved by using:

- Flexible mechanical fixing joints (discussed in section).

- Flexibility of thin glass.

Thin glass can be cold bent on site. The curvature of the glass can vary to adjust the grid difference. The difference in grid caused while constructing with bamboo can go up to 10cm. Hence glass can extend or bend and fixed accordingly. But glass also has limitations, i.e. it can bend only up to a certain amount without failing. If it is bent beyond its limit then it will crack because of its brittle nature. Hence the next section discusses the bending behaviour of glass.

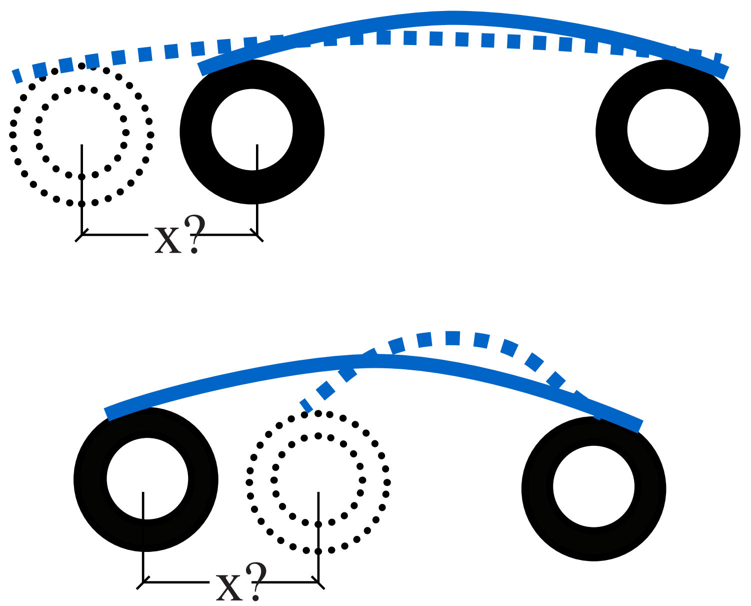


Figure 12.4e: Thin glass panels adjusted as per different bamboo grid construction

13 BENDING ANALYSIS OF THIN GLASS

Thin glass is bent as per the distance between the two bamboo poles. The bamboo may be constructed away or closer to the adjacent member and may not follow the exact grid distance. Because of high tolerances reaching up to 10cm, the flexibility of the glass is used and curvature of the glass is varying throughout the structure. The glass will flex or extend more if the bamboo is constructed away from the grid or it can curved more if the bamboo is closer to each other (figure 12.4e). Depending on the extent it can bend and extend the tolerances can be accounted. Hence with finite element analysis, the maximum curvature of thin glass is determined. The influence of glass thickness, PVB thickness and panel size is also evaluated. These parameters are considered to obtain maximum curvature. More the bending curvature, smaller will be the horizontal distance or span of the glass. Hence higher tolerances can be accounted if the glass can bend more.

13.1 MECHANICAL PROPERTIES OF THIN GLASS AND PVB

Cold bent glass; laminated with polyvinyl butyral (PVB) interlayer is used for this study. The stress limit of thin glass is considered to be 200 MPa. Deflection of glass in the x-axis is checked and compared with the stress developed. Because of large deflections, geometric non-linearity appears. The finite element analysis of laminated thin glass is done with the help of Ansys Workbench software. Thin glass was assigned isotropic material properties (figure 13.1). The PVB film is considered to have non-linear elastic hardening material property. The non-linear material properties of PVB were obtained from uni-axial bending experimental results (Molnár, Vigh, Stocker, & Dunai, 2012) (Figure 13.1c).

Both thin glass and PVB were modeled as shell elements. The type of contact created between the two elements is bonded. Symmetrical load was applied on both the sides of the glass to bend it. The load was applied on top surface 50mm on each side. The bottom surface was kept fixed at the center (figure 13.1).

Figure 13.1a: Double layer glass with PVB interlayer

Thin Glass Properties:
Density: 2.48g/cm³
Young's Modulus: 74GPa
Poisson's Ratio: 0.23

PVB Properties:
Density: 1.07g/cm³
Young's Modulus: 2.36MPa
Poisson's Ratio: 0.45

Figure 13.1b: Mechanical properties of thin glass and PVB

σ [N/mm²]	ε [-]	σ [N/mm²]	ε [-]	σ [N/mm²]
0.98	1.1	17.45	2.1	73.86
1.96	1.2	20.61	2.2	82.08
2.93	1.3	24.24	2.3	90.46
3.91	1.4	28.39	2.4	99.07
5.32	1.5	33.11	2.5	108.03
7.11	1.6	38.49	2.6	117.46
8.55	1.7	44.51	2.7	127.55
10.27	1.8	51.13	2.8	138.34

Figure 13.1c: Multi-linear elasticity of PVB
ref: (Molnár, Vigh, Stocker, & Dunai, 2012)

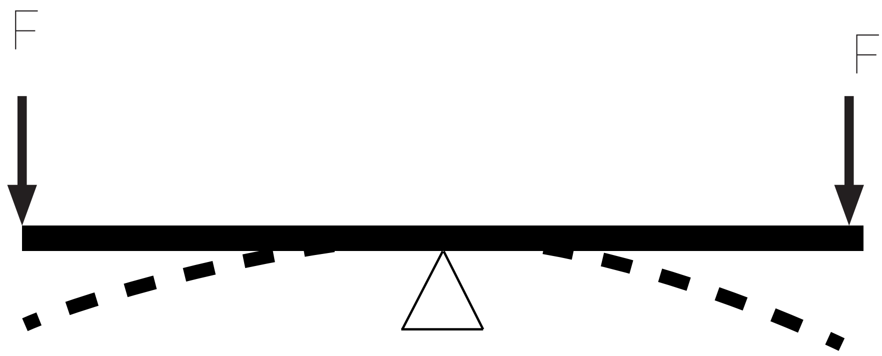


Figure 13.1d: Boundary conditions of thin laminated glass for FEA.

PARAMETRIC OPTIMIZATION USING FEA

13.2 THIN GLASS PANEL SIZE

The spacing and distances between the bamboo grid structure is dependent on the panel size. The maximum size of the panel available is 2mx 1.5m (Corning gorilaa glass). Maximum bending of panel was required to counter tolerances. Hence using FEM, panle sizes of length 1m x width 0.5m, length 1m x width 1m and length 0.5m x width 1m were evaluated to check maximum bending within its stress limit. Panel size of 1m x 1m showed maximum curvature.

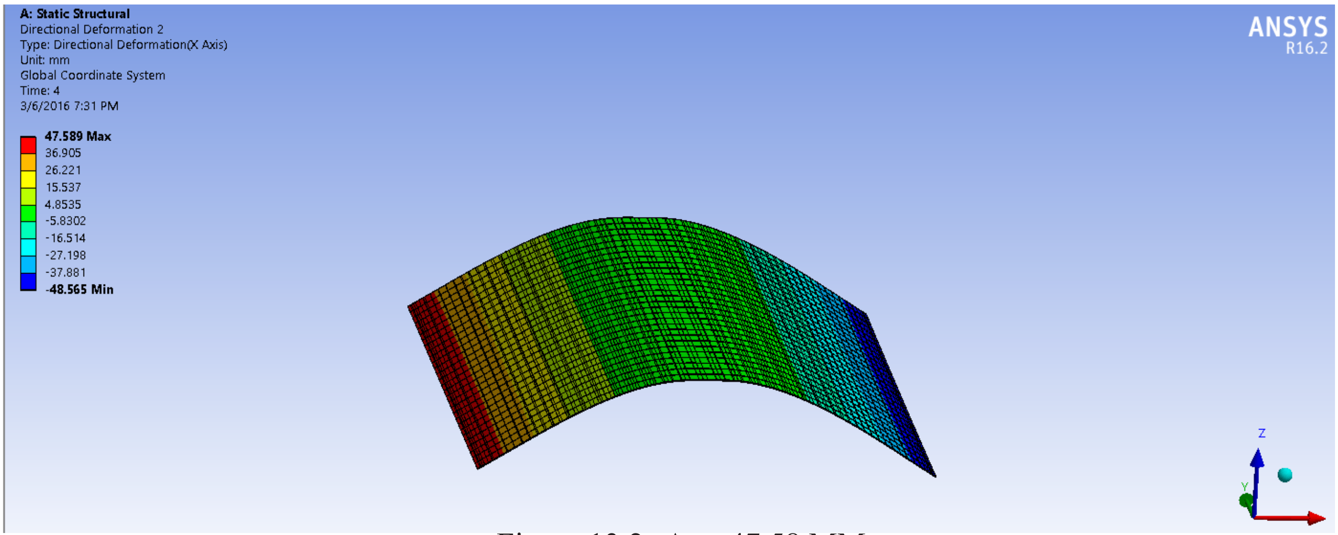


Figure 13.2a Δ_x = 47.58 MM

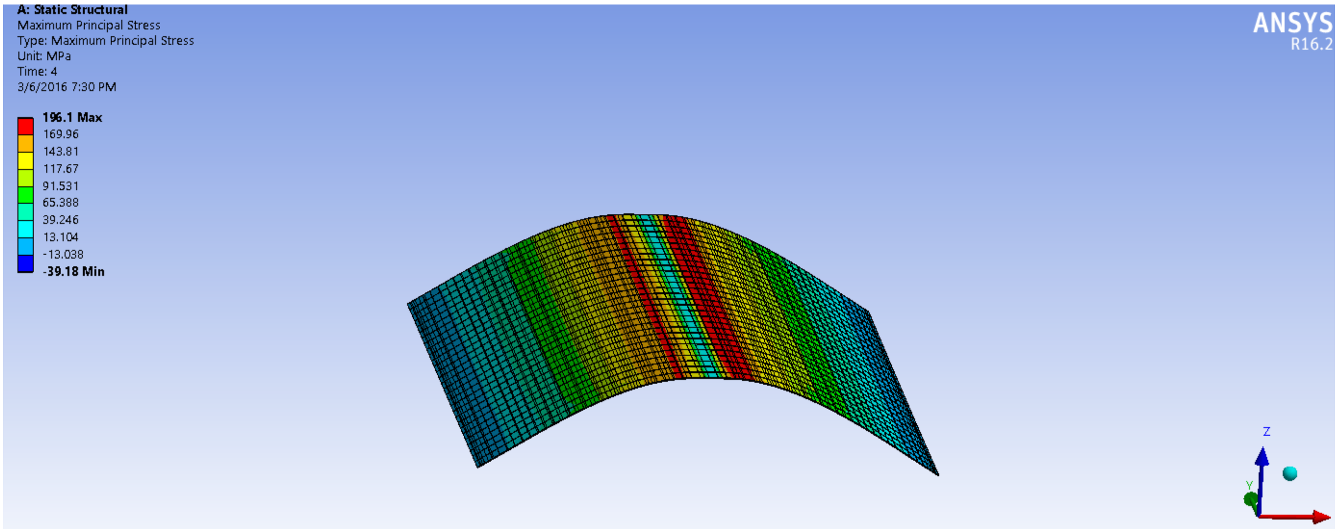


Figure 13.2bσ_{max} = 196 MPa

elements	Steps	load(N)	σmax (MPA)	Δ z (mm)	Δ x (mm)
3492	1	100	44.49	16.23	0.74
3492	2	200	82.33	27.62	2.03
3492	3	300	117.61	36.86	3.6
3492	4	400	150.95	45.56	5.94
3492	5	500	182.76	53.56	7.72
3492	6	600	213.21	60.96	10.02

Figure 13.2c: Panel size: 1000x500

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
3366	2	100	137.68	128.13	20.721
3366	3	150	195.42	169.87	36.92
3366	4	200	247.55	204.32	54.63
3366	3	300	337.96	255.8	88.35
3366	4	400	414.26	292.6	120.17

Figure 13.2d: Panel size: 500x1000

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
4379	1	100	71.45	81.55	8.43
4379	2	200	126.86	133.89	22.41
4379	3	300	174.6	176	38.93
4379	4	350	196.1	193.94	47.58
4379	4	400	216.24	210.12	56.29

Figure 13.2e: Panel size: 1000x1000

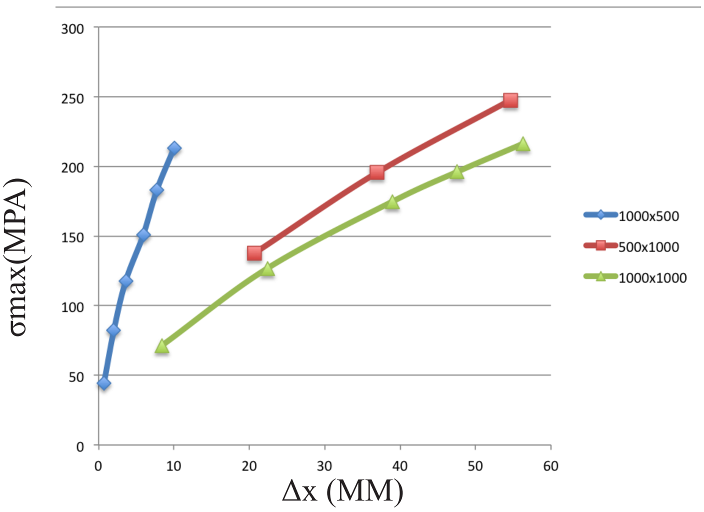


Figure 13.1f: Panel size comparison.

13.3 THIN GLASS THICKNESS

Thickness of thin glass ranges from 0.56-2mm. Glass thickness of 0.56mm, 1mm and 2mm was evaluated to check the bending behaviour. Thinner glass bends more before reaching its yield limit. Glass thickness of 0.56mm is selected for cladding the bamboo strcture. This is because glass should bend as much as possible to match the distance between two bamboo elements in the gridshell. The size of the panels used was 1x1m as concluded in section 13.2. Only the thickness of the panels were varied and compared.

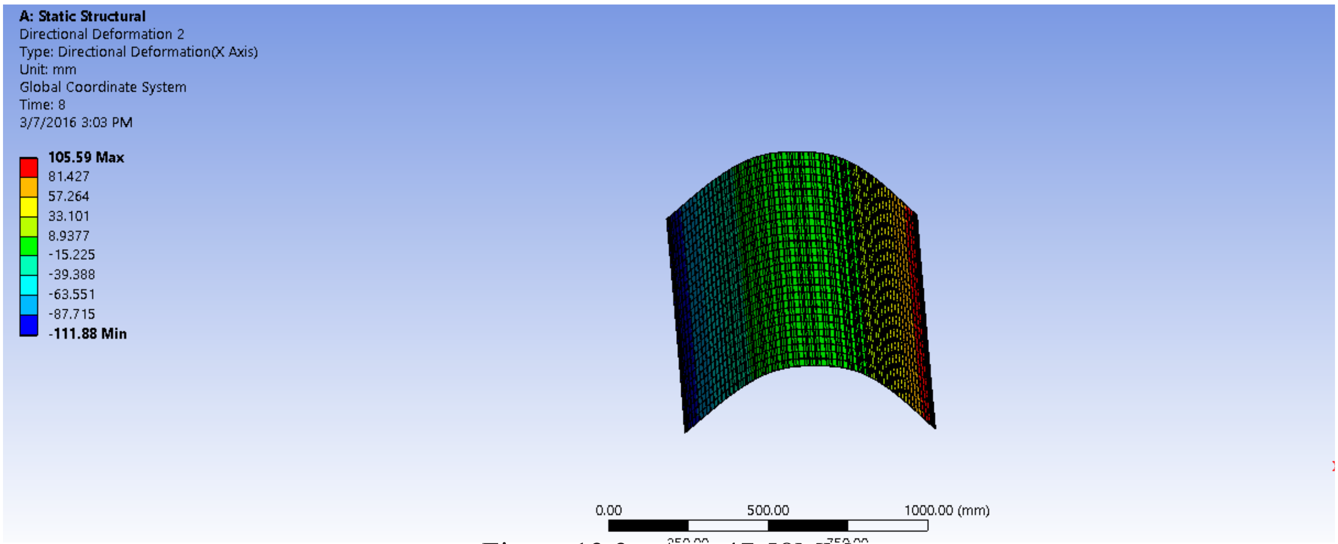


Figure 13.3a: $\Delta_x = 47.58$MM

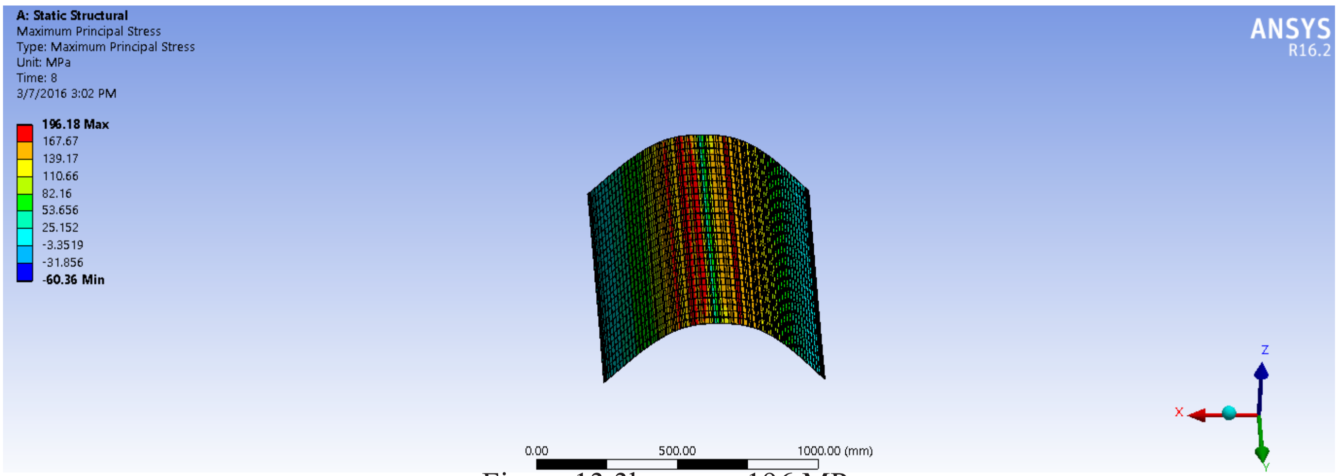


Figure 13.3b: $\sigma_{max} = 196$ MPa

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
4379	5	50	68.09	125.84	19.92
4379	6	100	119.75	196.72	48.81
4379	7	150	161.76	245.66	78.39
4379	8	200	196.18	280.16	105.59

Figure 13.3c: Panel thickness: 0.56-0.38-0.56

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
4379	1	100	71.45	81.55	8.43
4379	2	200	126.86	133.89	22.41
4379	3	300	174.6	176	38.93
4379	4	350	196.1	193.94	47.58
4379	4	400	216.24	210.12	56.29

Figure 13.3d: Panel thickness: 1-0.38-1

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
4379	4	400	90.246	64.47	5.13
4379	6	600	128.47	87.2	9.38
4379	8	800	164.42	107.64	14.27
4379	9	900	181.75	117.2	16.93
4379	10	1000	198.52	126.42	19.68

Figure 13.3e: Panel thickness: 2-0.38-2

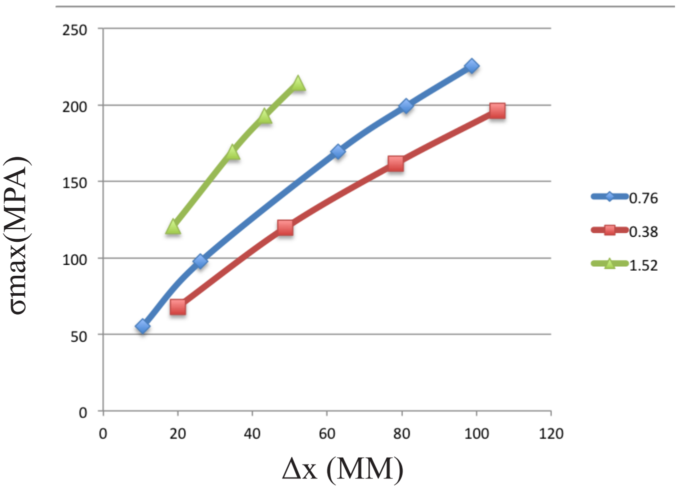


Figure 13.3e: Panel thickness comparison.

13.4 PVB THICKNESS

PVB foil (polyvinyl butyral) is used to laminate two layers of glass together. The thickness of PVB foil is 0.38mm. For safety. purposes multiple foil can be used to laminate glass. If insets like metal or composite is partially laminated in between the two layers of glass, then PVB is used to maintain the overall thickness. Hence 3 layers of PVB foil is needed if an insert needs to be laminated along with glass. In this case metal insert is needed for connecting glass to the clamps (Section 14.6). Lesser the number of PVB lamination foils, more is the flexibilty of laminated glass. A single layer of PVB foil will bend the panel more. The thickness of 3 layers of PVB is 1.14mm.

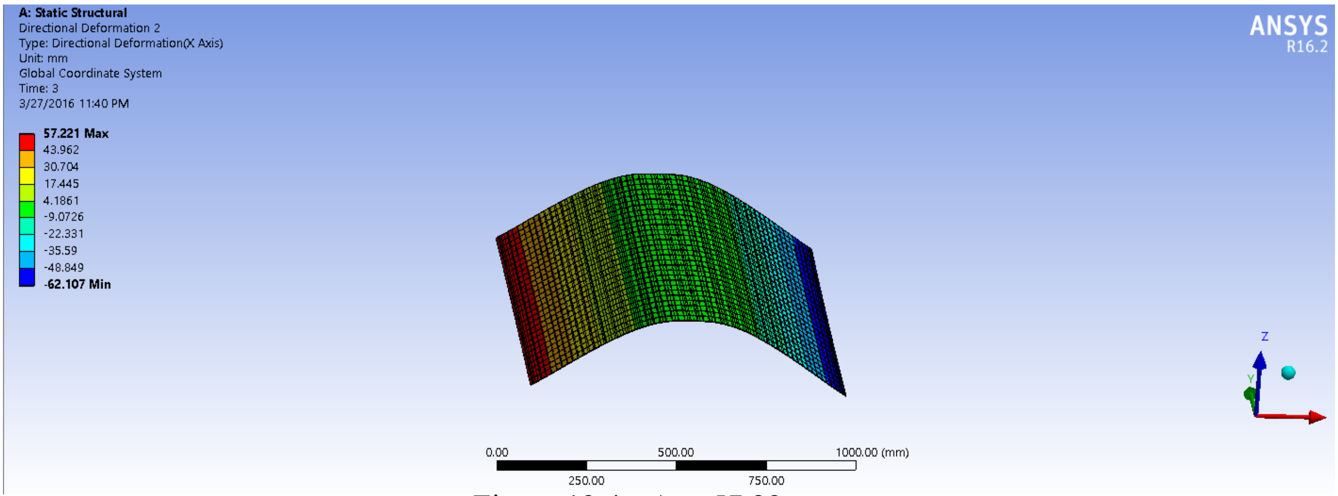


Figure 13.4a: Δ_x = 57.22mm

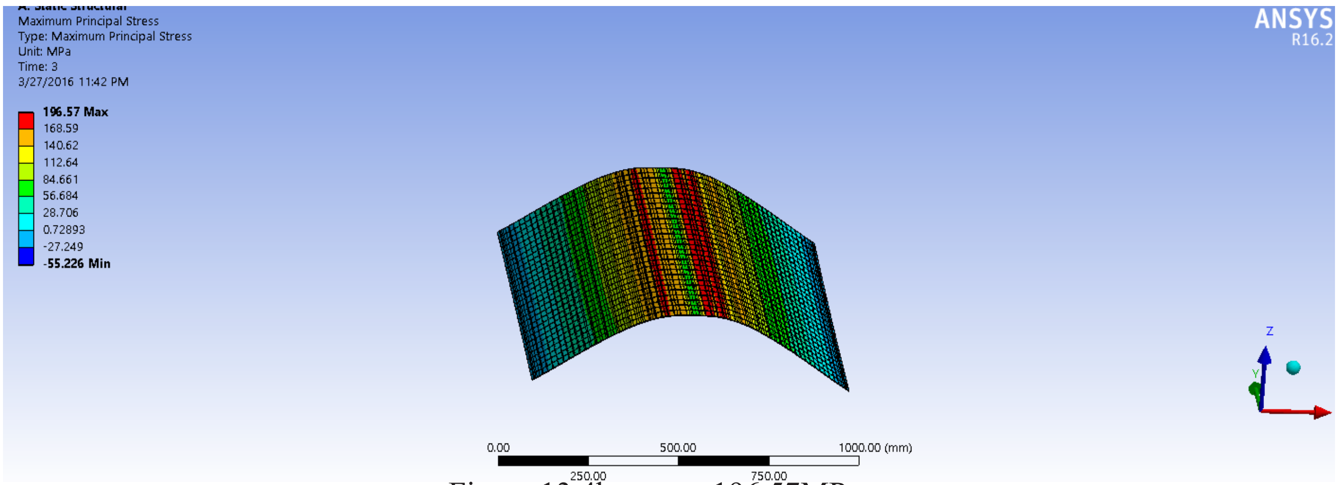


Figure 13.4b: σ_{max} = 196.57MPa

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
4379	5	50	55.11	92.85	10.51
4379	6	100	97.82	147.17	26.12
4379	8	200	169.43	225.04	62.83
4379	4	250	199.04	253.02	81.03

Figure 13.4c: Panel thickness: 0.56-0.76-0.56

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
7030	1	100	78.693	102.49	12.02
7030	2	200	142.06	168.54	32.91
7030	3	300	196.57	219.47	57.221
7030	3	350	220.77	240.28	69.83
7030	4	400	242.69	258.12	82.01

Figure 13.4d: Panel thickness: 0.56-1.14-0.56

elements	Steps	Load(N)	σmax(MPA)	Δ z (mm)	Δ x (mm)
4379	2	200	120.57	132.21	18.844
4379	3	300	169.67	176.17	34.64
4379	4	350	192.74	196.13	43.27
4379	4	400	214.42	214.1	52.2

Figure 13.4e: Panel thickness: 0.56-1.52-0.56

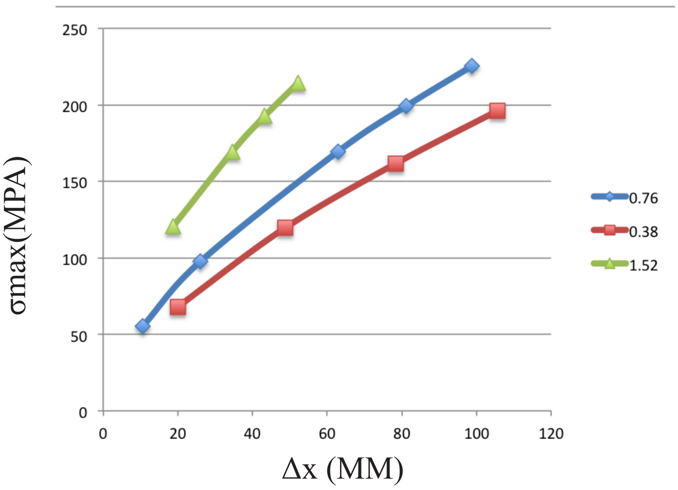


Figure 13.4f: PVB thickness comparison.

13.5 CONCLUSION

In the most optimum condition, thin glass will be bent at a curvature of 731.51mm. But this is difficult to meet for the entire roof structure. As bamboo is used to construct the grid on which the glass is clad, the tolerances are very high in this case. 10cm of total tolerance is considered (as experienced during the construction of ecological children's center by 24H architects) (section 4.1). When there are errors while constructing the bamboo structure, the bamboo can move closer or farther by 10cm from its adjacent member. Flexibility of thin glass is used to overcome this flaw. Using FEA, the bending curvature of thin glass was analyzed. This was needed as it can extend and bend only to a certain limit.

The results show that 45% of the errors can be accommodated by using this method. When bamboo is shifted 10cm closer to its adjacent member, glass is bent more to a curvature of 556.38mm. When bamboo is farther away by 10cm, glass is bent to a curvature of 1212.94mm. It can extend further to form a flat panel but it is important to keep the water flowing in both the directions.

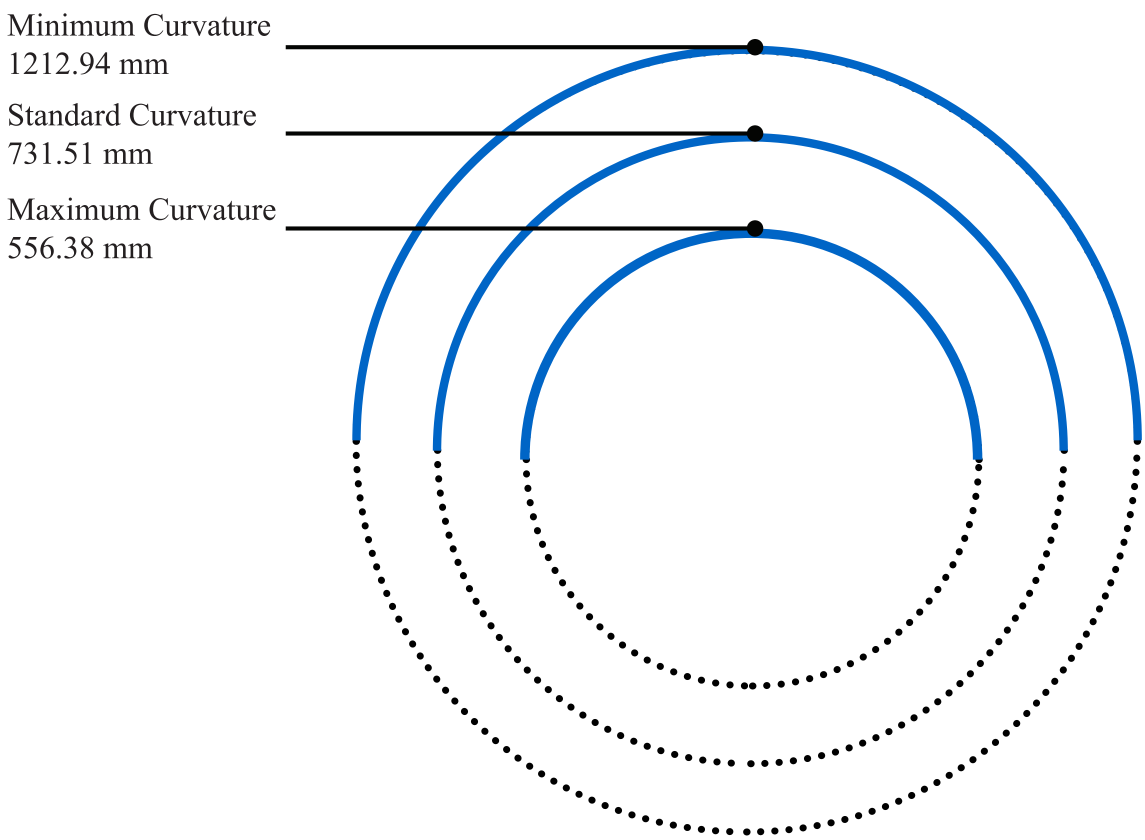


Figure 13.5a: Thin glass maximum minimum and standard bending radius curvature

Glass Panel
Size: 1000x1000
Glass thickness: 0.56mm
PVB thickness: 1.14mm

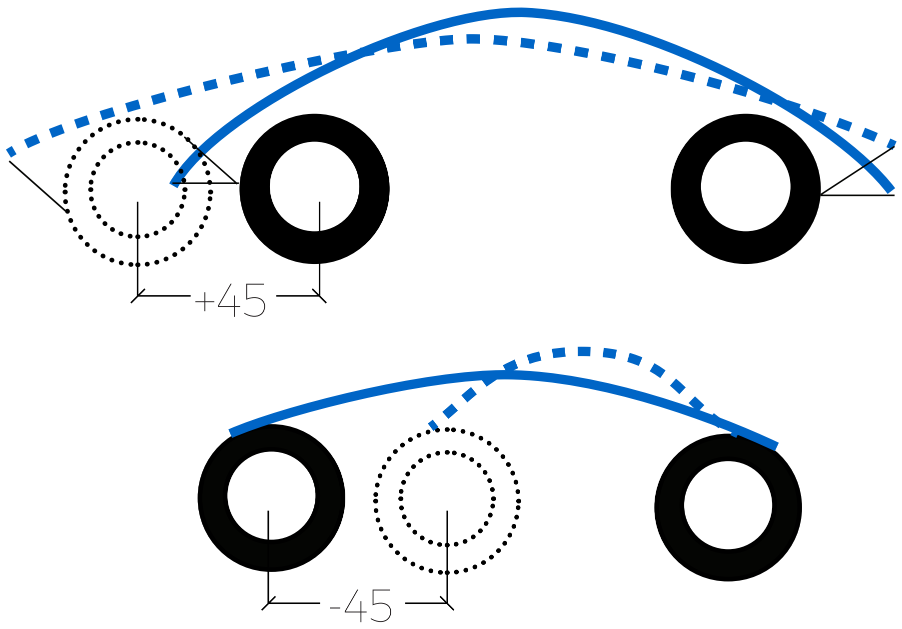


Figure 13.5b: Tolerance in bamboo grid accounted by flexibility of thin glass.

CONNECTIONS AND DETAILS

14

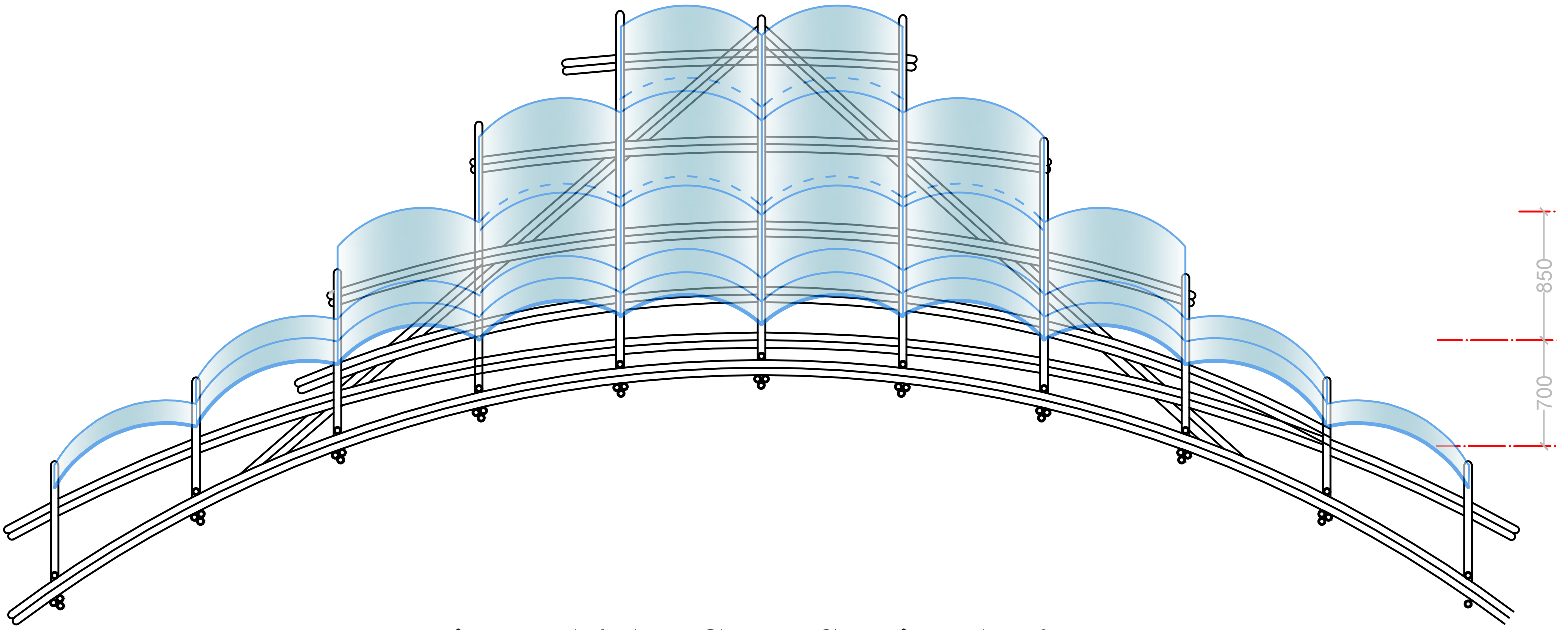


Figure 14.1a: Cross Section 1:50

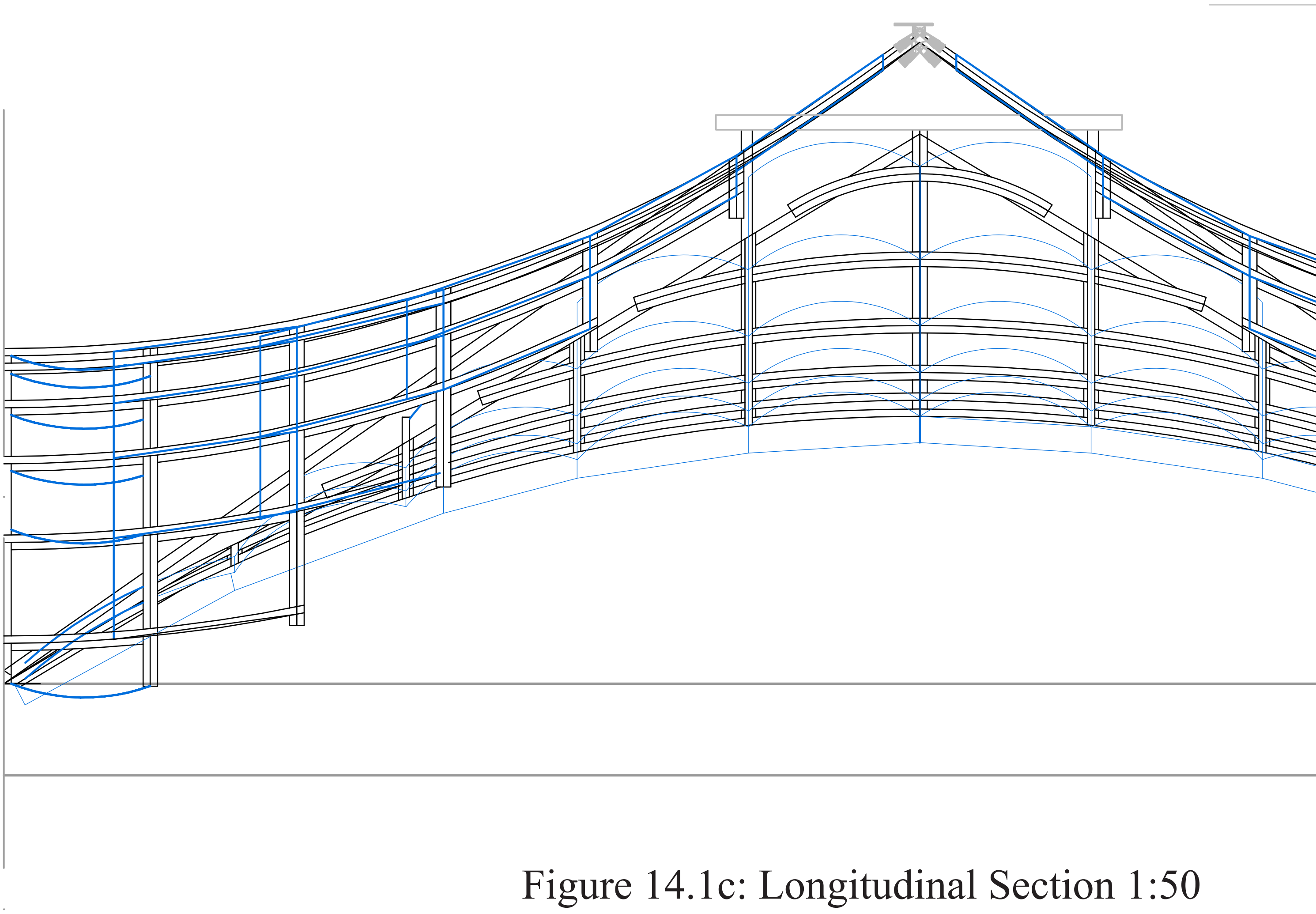


Figure 14.1c: Longitudinal Section 1:50

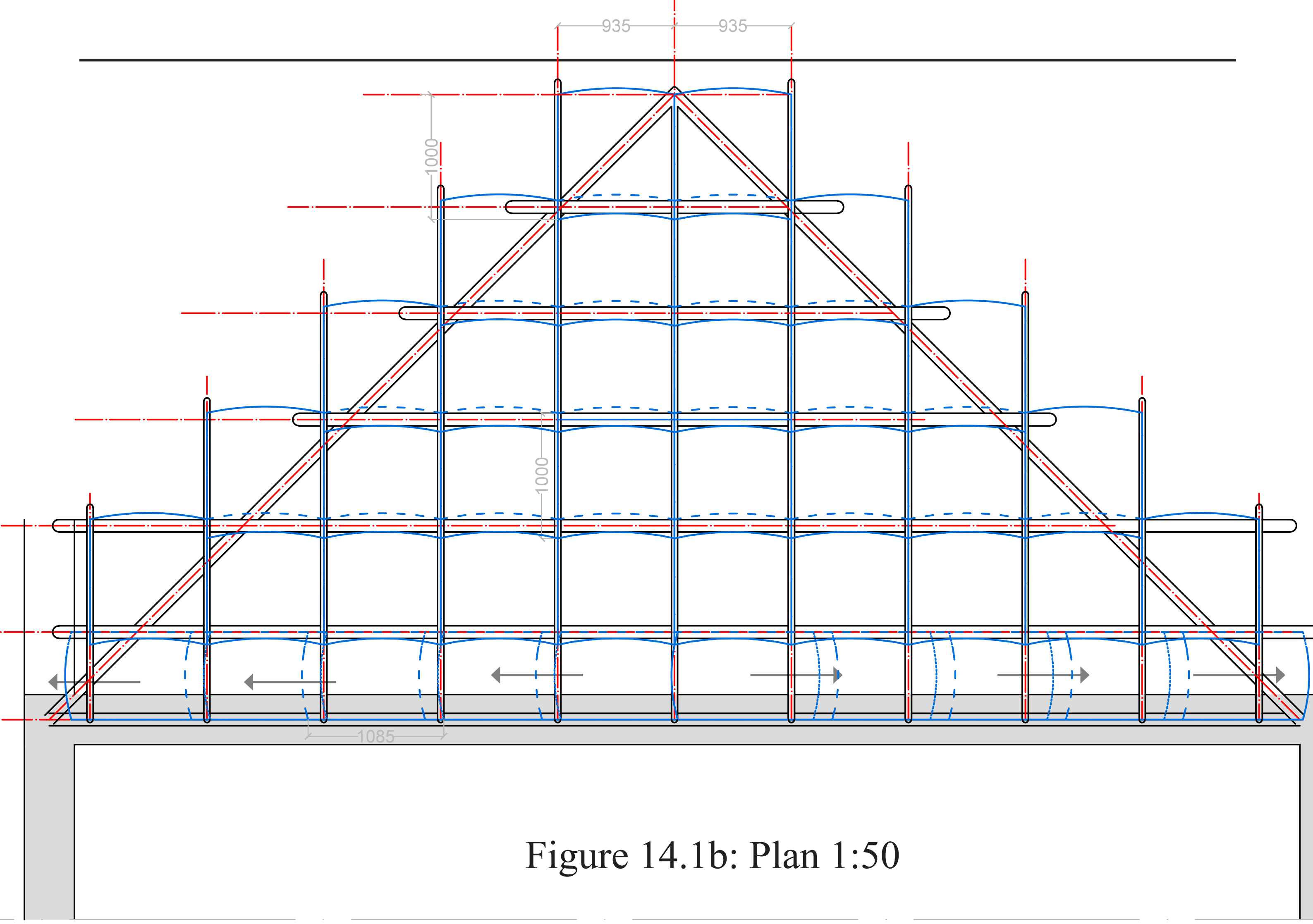
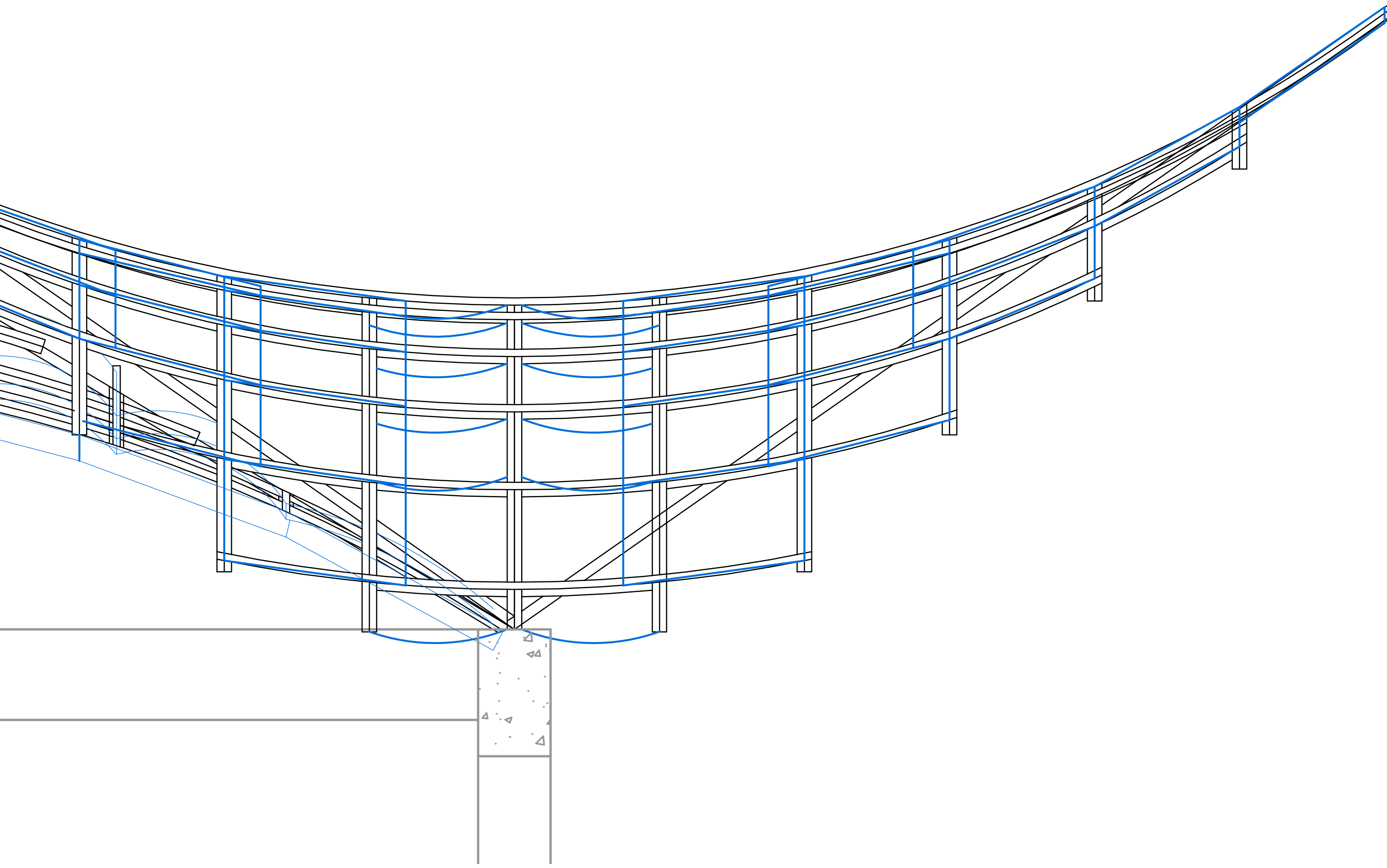


Figure 14.1b: Plan 1:50



STRUCTURAL GLAZING TAPE

VHB™ tape from 3M® is one of the well know companies with wide range of structural tape for different kind of materials and structures. The tape consists of a foam and an adhesive layer. The adhesive layer will counter static load while the foam will take care of dynamic loading.

The minimum tape width for is dependent on three factors (VHB™ 3M® technical guide):
- The strength of the tape
- Force acting on the fixture (indirectly the tape).
- Size of the panel

To find out the width of the tape, the company has provided a simple calculation:

$$\text{Tape width(mm)} = \frac{\text{0.5 x panel short length edge x wind load (kPa)}}{\text{Tape design strength (85kPa)}}$$

As thin glass is cold bended and it is elastically bent, The reaction force from the glass should also be taken into consideration.
The reaction force from the glass is minimum 300N (Figure 14.7f).
The panel size is 1000mmx1000mmx1.14mm.
Force per unit area = 300/0.00114 = 263157 N/m^2
Wind load + reaction force = 1500+263157 N/m^2 = 27.81kPa.
The total width of the tape will be 163mm.

Site Glazing: The cold bending of glass is done on site and then fixed. This is done because of varying curvature required as per bamboo grid distance. This kind of fabrication technique is not recommended for 3M® (VHB™ 3M® technical guide). The workplace to fix the tape and glazing has to be free from dust. Constant temperature level is also required for setting time. As constant conditions cannot be met on site, use of structural glazing tape for fixing glass panels is not feasible for this project.
Further research needs to be done on adhesive connection for cold bended laminated glass. The influence of reaction force acting on the adhesion or the tape needs to be studied.
For the glass to stay in position, both tensile and compression force should be taken care by the connection. The adhesion of the tape to counter tension might weaken over a period of time, especially in humid climatic conditions.

LASHING AND BOLTING METHOD

The technique of using ropes and bolts for connection is explained in section 5.1 However these connection systems are not used for this project even though it is a common technique. This type of connection makes it easy to deal with tolerance issue. But both the connections are very weak in terms of durability. It decreases the durability of the entire structure because of wear and tear. The strength of the joint also depends on the craftsmanship and same quality is not achieved.

There are many research papers studying the strength of bolted and lashing joints. In a bolted connection, the joint fails because bamboo splits easy. The fibres in the bamboo are distributed only in one direction, unlike wood. Hence bamboo splits easily. Whereas, the lashing joint connected by natural fibre ropes may be strong in the initial stage. But the strength decreases periodically as the ropes becomes loose. To maintain the strength composite fibres have been tried. But it is not recommended by many bamboo experts. When bamboo is exposed to water, it will not harm the bamboo if there is enough ventilation to dry. But once resin is used with ropes, the moisture will be captured and decay the bamboo poles.

For this project, mechanical fixtures like aluminium clamps have been explored and discussed in next section.

Figure 14.1d:Bamboo connection using bolts
ref: (Chris Davies)

Figure 14.1e: Bamboo connection using hemp rope
ref: (Jaap Overal)

Figure 14.1f: Bamboo connection using composite rope
ref: (Jaap Overal)

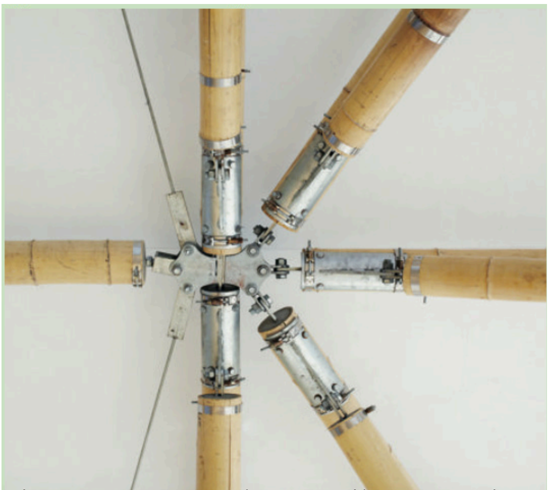


Figure 14.1g: Bamboo tensile connection using clamps
ref: (Markus Heinsdroff)

14.2 MECHANICAL FIXTURES

Thin glass is connected to a single layer to bamboo, which is pre-bent with concave curvature (figure 14.1e). Bamboo metal clamps have been develeped by Markus Heinsdroff for tensile connection (section 5.1). But these clamps are for straight bamboo. As pre-bent bamboo is used for the roof structure, the clamps need to be double curved to attach to the bamboo wall surface. Hence the metal clamp was altered to be suitable for pre bent bamboo.

In the first option, a cross clamp was developed which was adjustable. Cross clamp was developed so that it is fixed to a double curved surface by two single curved surfaces. The uneven outer surface of bamboo, tapering diameter were two main aspects considered. The cross clamp was deconstructed and hinged to adjust according to the bamboo outer body surface (figure 14.2c and figure 14.2e). However it was difficult to expand this component to connect to thin glass.

The second option was to use clamps which did not need to be double curved as the curvature along the length can be negligible when using a thinner clamp. In this case the uneven surface of bamboo will be accounted by using a layer of soft material like silicon below the clamp where it is in contact with bamboo. The extension of bamboo clamp is connected to glass clamp. The extension allows rotation of glass clamp. This rotation was required as the curvature at which the glass is not constant. The angle at which the glass is fixed to the bamboo clamp changes depending on the curvature of glass (figure 14.3b). This joinery needed further refinement as there were too many components and parts in this system and glass to glass connection was not feasible in this option.

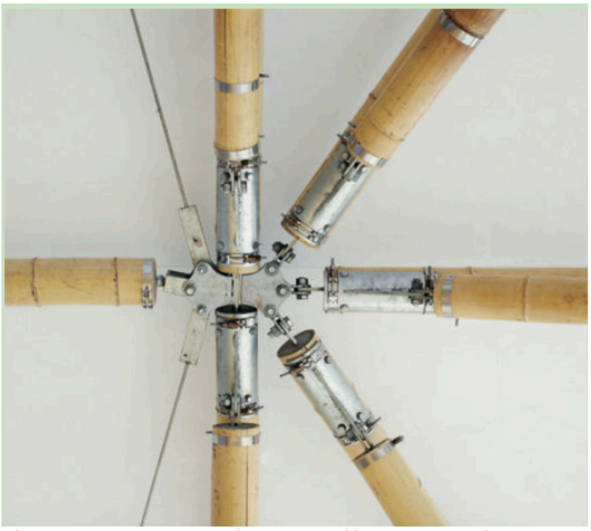


Figure 14.2a: Bamboo tensile connection using clamps (Markus Heinsdroff)

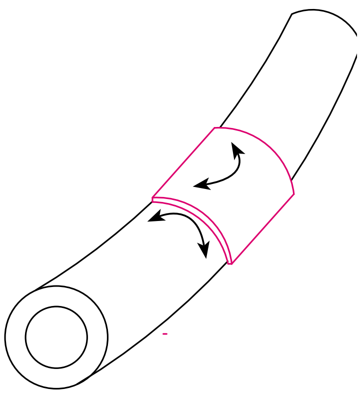


Figure 14.2b: Clamp needs to be double curved as pre-bent bamboo used.

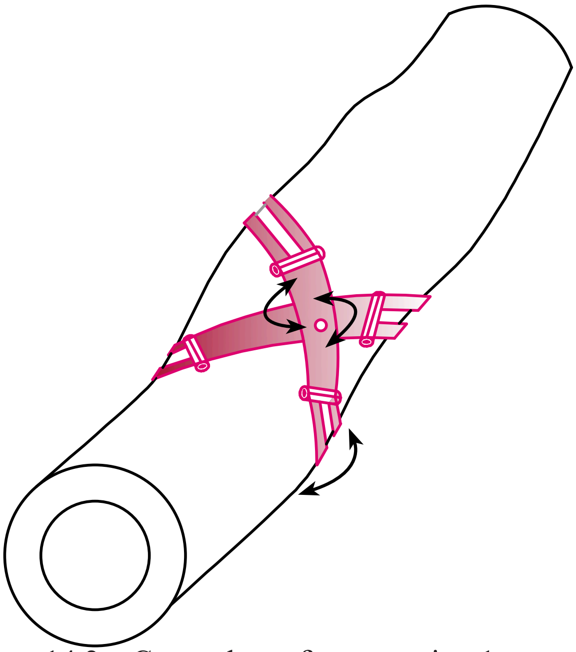


Figure 14.2c: Cross clamp fixture option 1

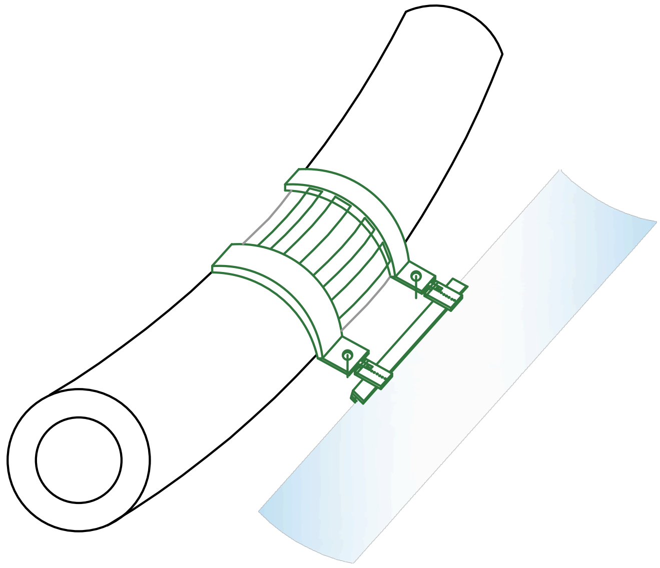


Figure 14.2d: Clamp fixture option 2

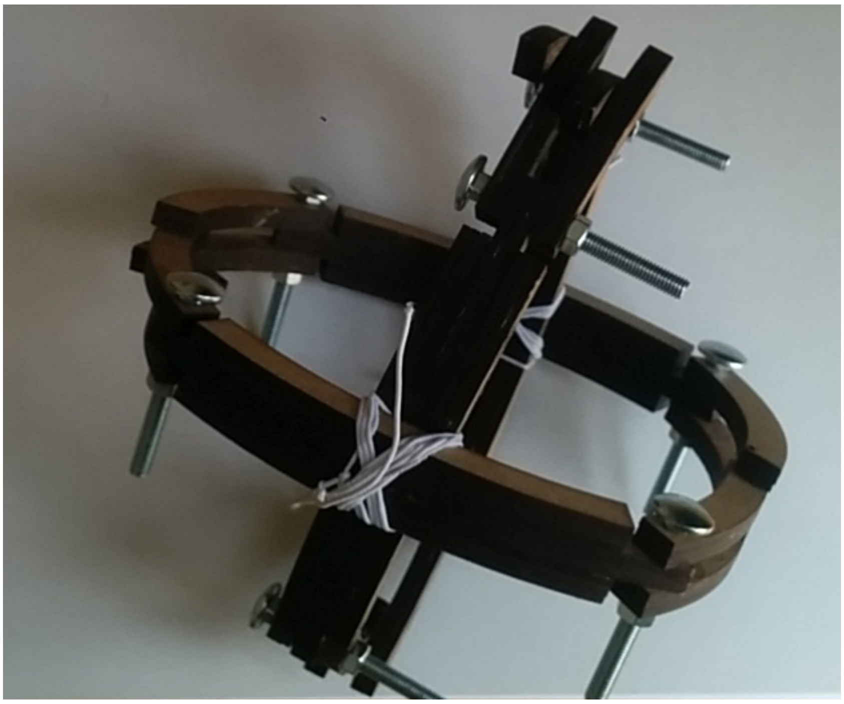


Figure 14.2e: Clamp wooden model scale1:1 option1

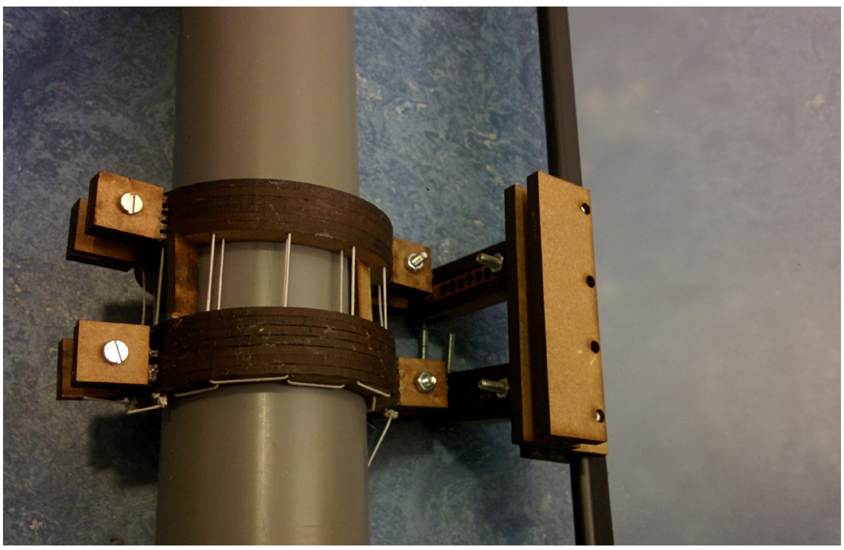


Figure 14.2f: Clamp wooden model scale1:1 option2

14.3 MECHANICAL FIXTURES

WATER PROOF / WATER TIGHT
- Overlaping panels (both directions)
- Water tight joints

TOLERANCE
- Varying bamboo grid distance

DEGREE OF FREEDOM.
- Allow glass to extend or bend.
- Vertical movement of glass clamps required.

CLAMPING ONLY IN ONE DIRECTION (TWO PARALLEL SIDES)
- To reduce labour, cost and avoid complexities.

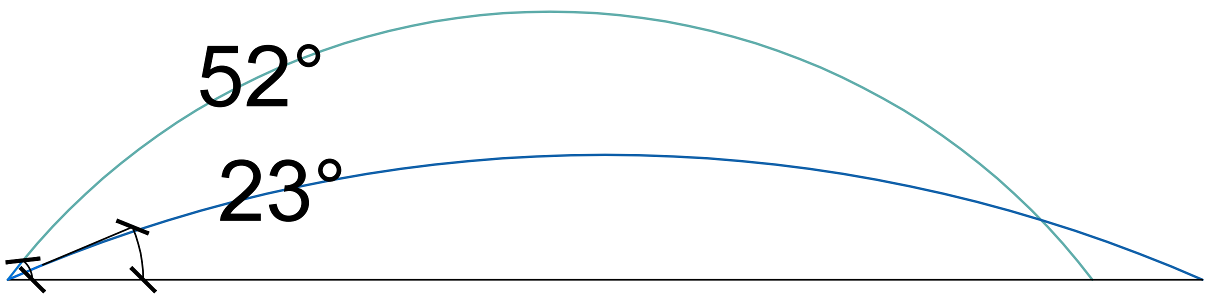


Figure 14.3a: Maximum and minimum curvature of glass. Possible angle ranges from 23º-52º that glass can be fixed to the clamps.

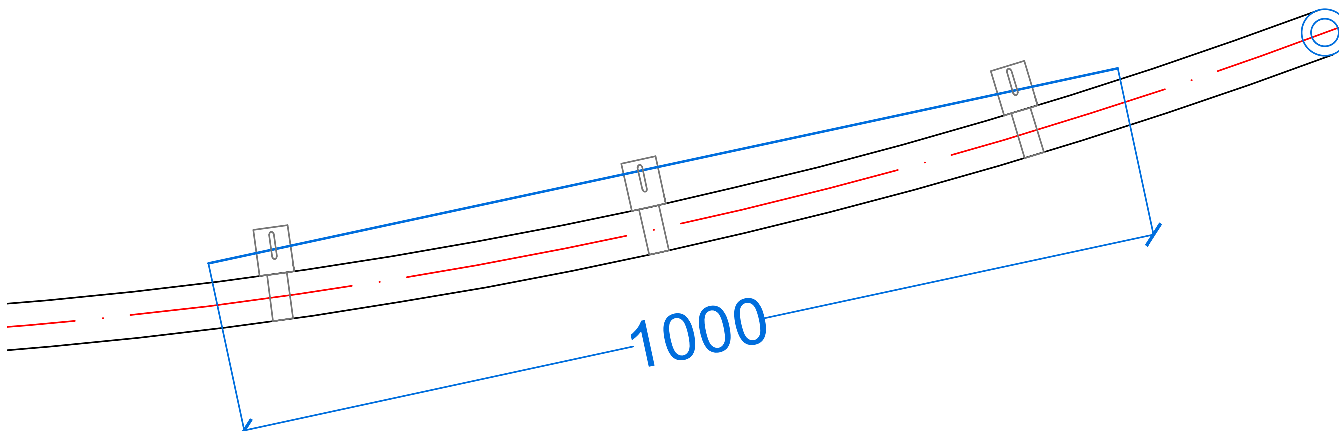


Figure 14.3b: Glass panels attached at different levels.

14.4 CYLINDRICAL CURVATURE - JOINERY OPTIONS

OPTION 1A

Glass should be clamped only on two sides. It can be clamped either on th curved edges (Figure 14.4a) or on straight edges (Figure 14.4b). If glass is fixed on the curved edge, then first the clamps needs to be bent according to the bamboo grid distance and then place the glass in between (figure (14.4c). This increases labour work and time. Hence in this case the glass should be fixed on the straight edges. By doing this, it gives freedom to bend and extend the glass as required.

- ✗ WATER PROOF
- ✗ TOLERANCE
- ✗ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

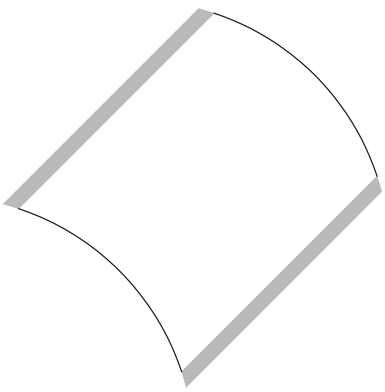


Figure 14.4a: Glass clamped on curved edges

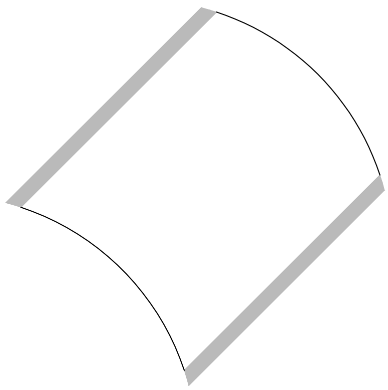


Figure 14.4b: Glass clamped on straight edges

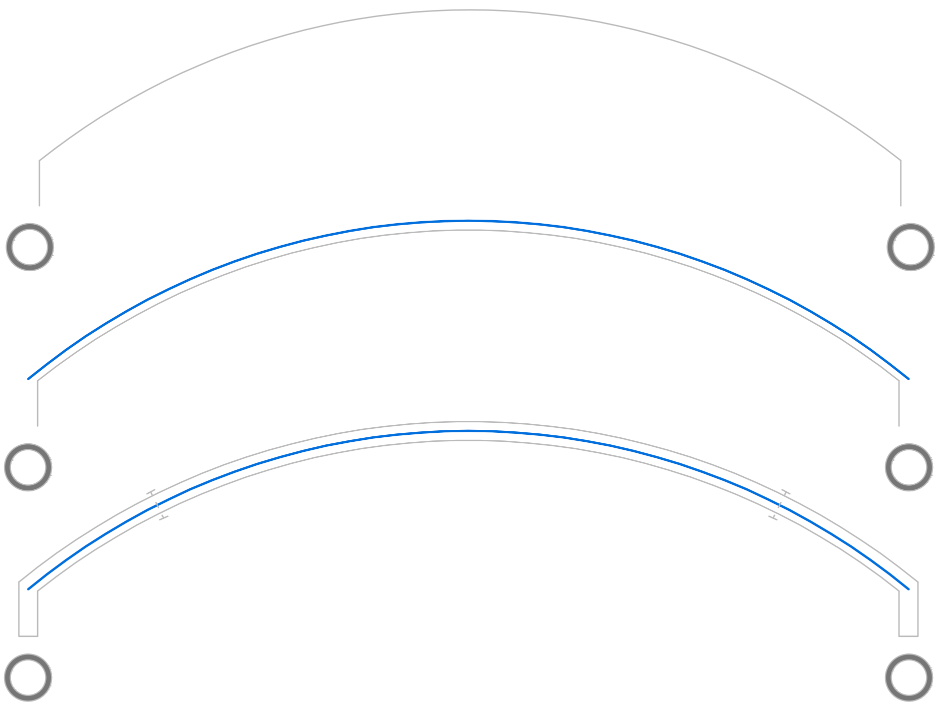


Figure 14.4c: Assembly sequence

OPTION 1B

Glass clamps are fixed to bamboo clamps. This can be done either fixing the glass clamps to convex bamboo grid members (Figure 14.4e) or concave grid members (Figure 14.4f). The length of the glass panel is fixed, which is 1000m. The width is kept varying by bending and extending the panels. If it is connected to convex members then the distance between bamboo grid has to be exactly constructed as 1000mm (Figure 14.4d). As the glass cannot adjust in that direction. This level of precision is not usually acquired. Hence glass panels are connected to concave bamboo grid members.

- ✓ WATER PROOF
- ✗ TOLERANCE
- ✓ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

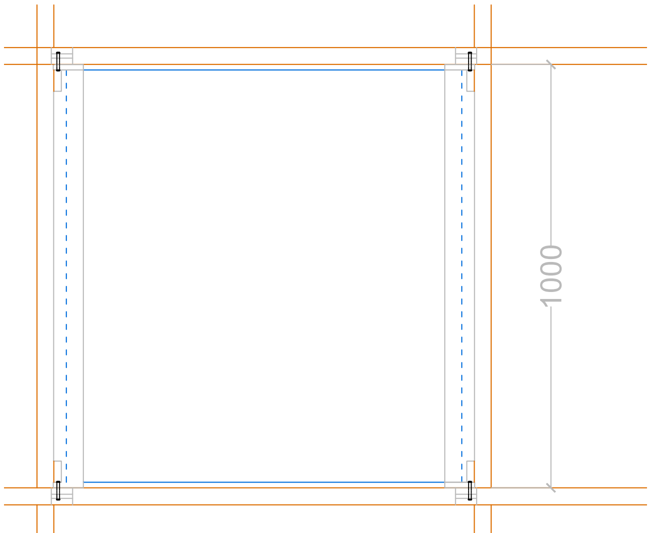
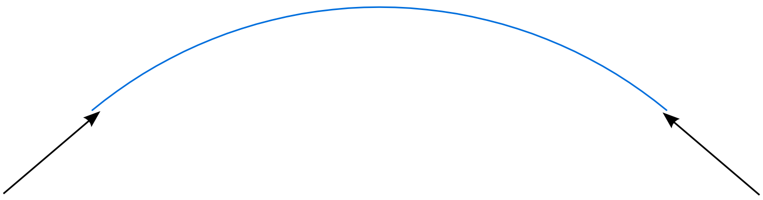


Figure 14.4d: Plan showing glass clamped on straight edge and fixed to convex arched bamboo.



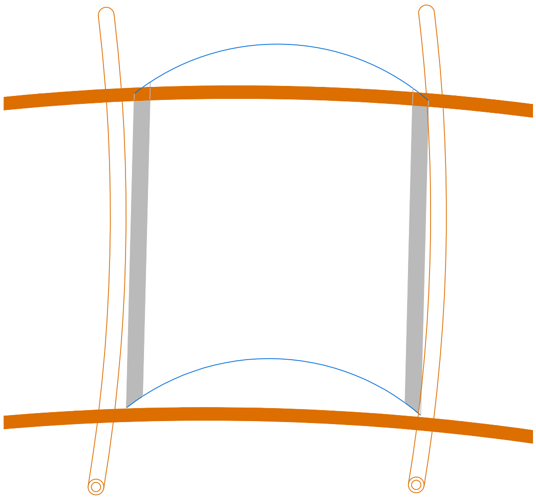


Figure 14.4e: Glass fixed to convex arched bamboo grid members

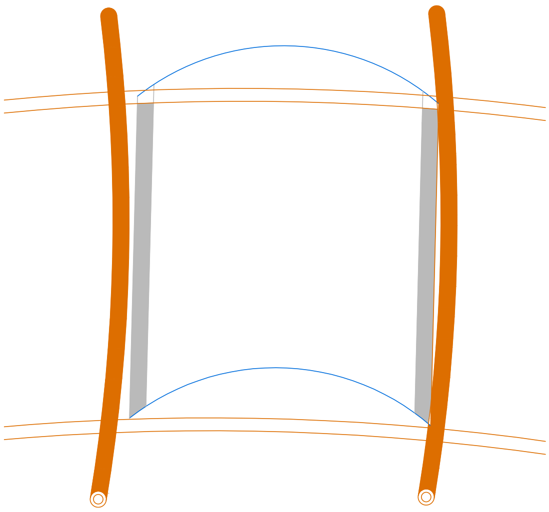


Figure 14.4f: Glass fixed to concave arched bamboo grid members

Tolerance on all three directions have been resolved. The reason and the type of tolerance that occur is discussed in section 12.5. In x-axis, the tolerance is accounted by bending of glass. In y-axis, because of the overlap of the glass it is taken care. The overlap between the two glasses is 200mm. And in the z-direction, the vertical movement allowed in the mechanical fixture will solve the problem.

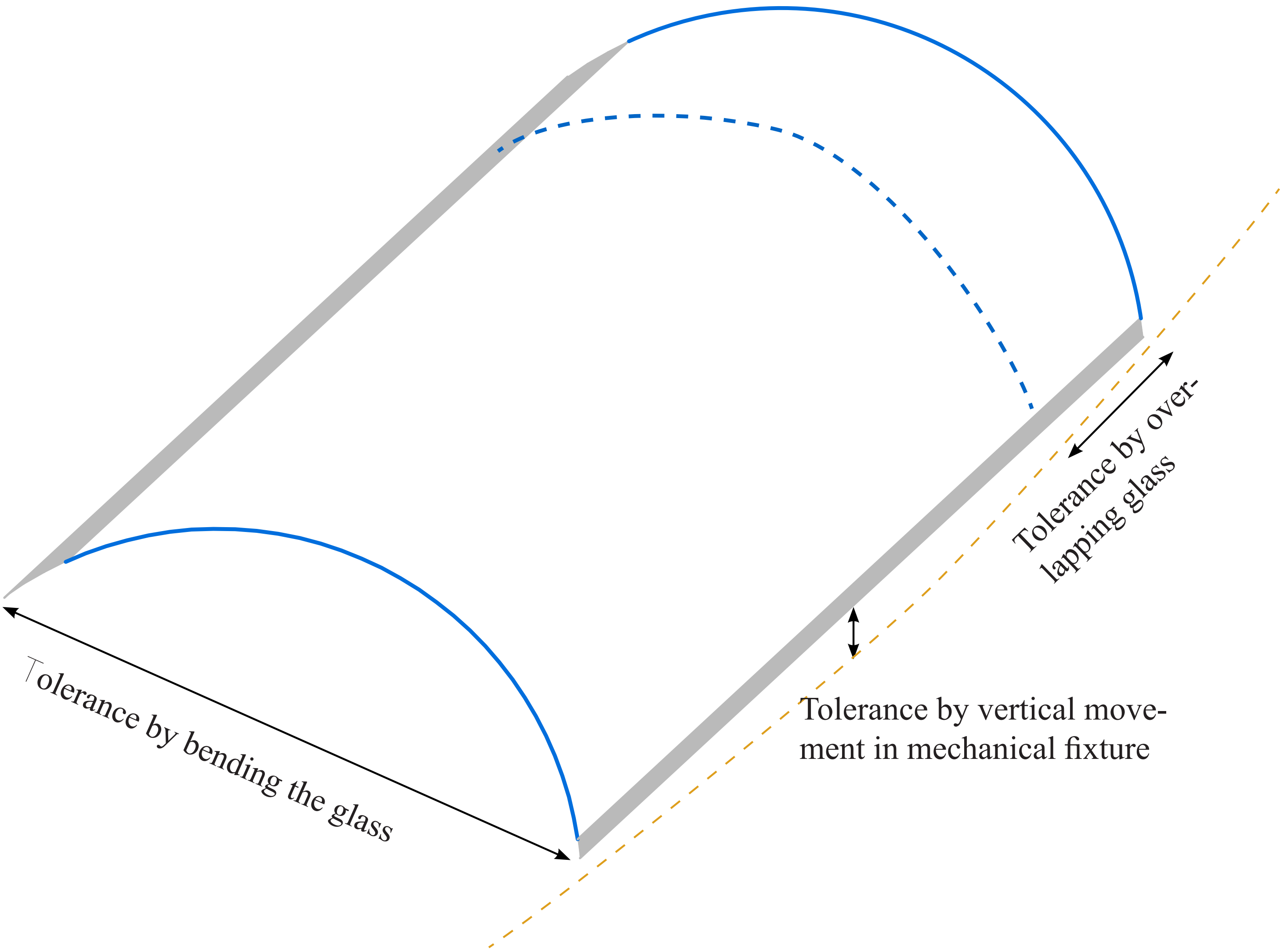


Figure 14.4g: Tolerance accounted in all 3 directions

OPTION 2

Clamps connected to bamboo extend to connect with glass clamps. Panels are curved cylindrically in the same direction. The angle at which the glass is fixed, is different for each panel and depends on bamboo grid distance. This requires independent rotation of the clamps. Adjacent clamps connected to each other may not have the same fixing angle. Hence the two glass clamps are not kept fixed but needs to be hinged. Or it can be welded and fixed after the angle of the glass clamp is positioned (Figure14.4i). This does not lead to a waterproof joint. Waterproofing is achieved only in one direction where the panels are overlapping each other (Figure14.4j). Hence other options are explored.

- ✗ WATER PROOF
- ✓ TOLERANCE
- ✓ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

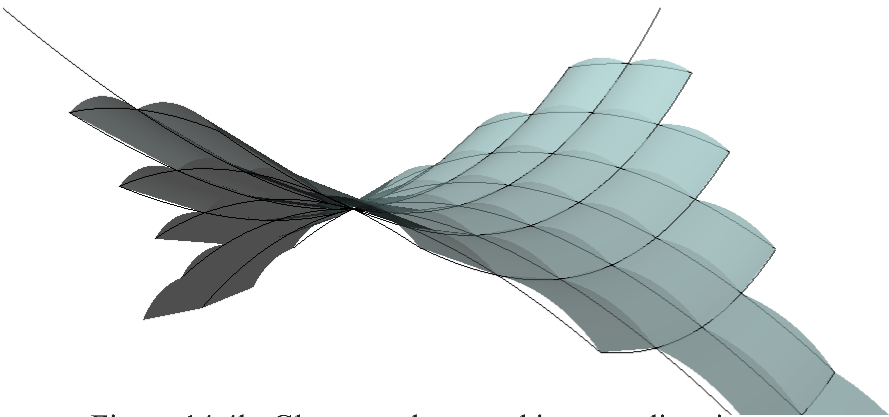


Figure 14.4h: Glass panels curved in same direction.

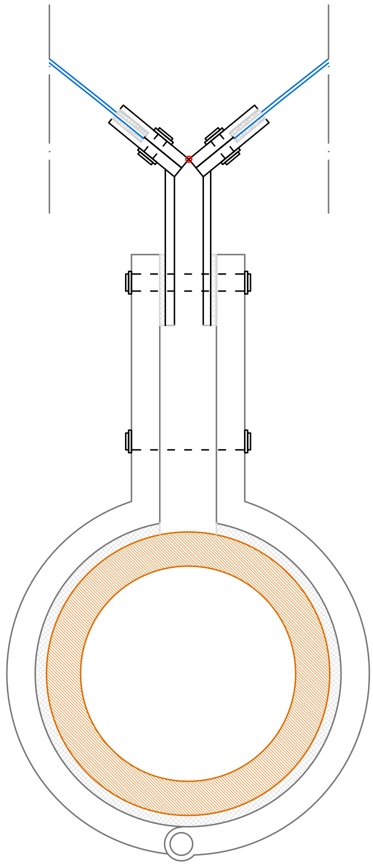


Figure 14.4i: Glass clamps hinged or welded together.

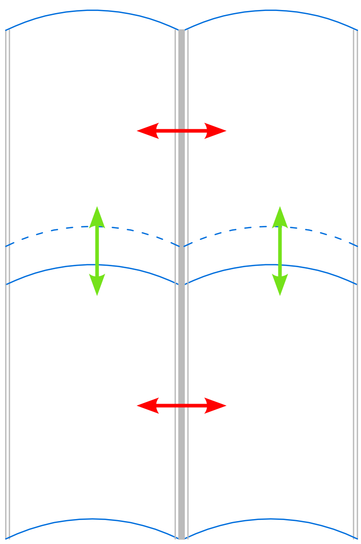


Figure 14.4j: Waterproofing only in one direction, where panels overlap.

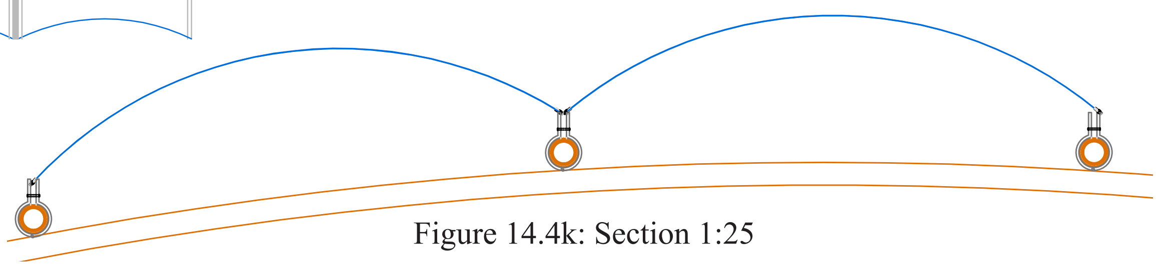


Figure 14.4k: Section 1:25

OPTION 3

This type of connection between the panels would have been a good solution for thermal and acoustic insulation. But the main problem in this sytem is that the total thickness of the system increases and overlapping is not possible. Also complexity increases in terms of fixing four clamps together and allowing adjustments. The fixing shown in the detail (Figure14.4m) is a fixed connection. This will not allow the glass to bend. Hence his kind of a connection would be ideal if the gridshell is made up of steel. But in this case for bamboo gridshell, this system cannot be further resolved.

- ✗ WATER PROOF
- ✗ TOLERANCE
- ✗ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

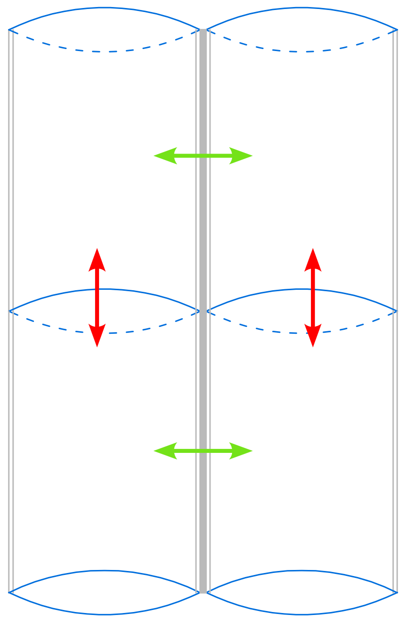


Figure 14.4l: Waterproofing only in one direction.

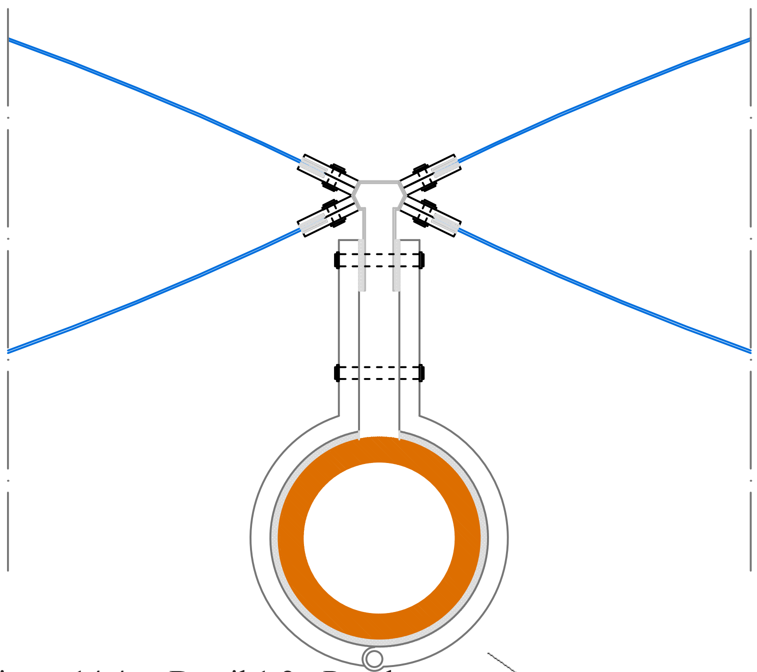


Figure 14.4m: Detail 1:2 - Panels are fixed in order to create water tight joint

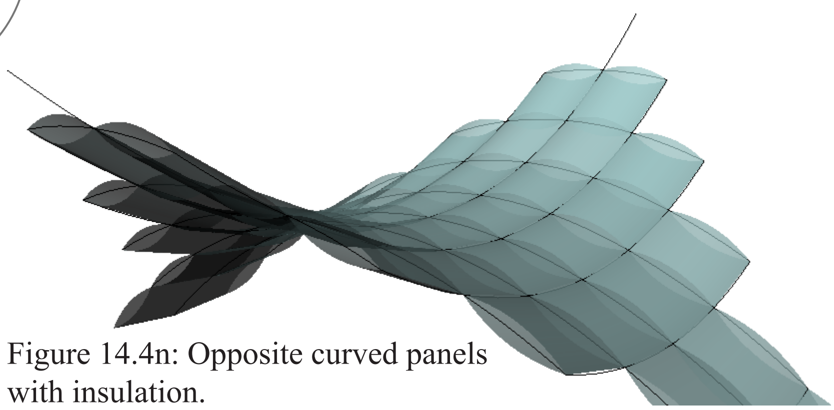


Figure 14.4n: Opposite curved panels with insulation.

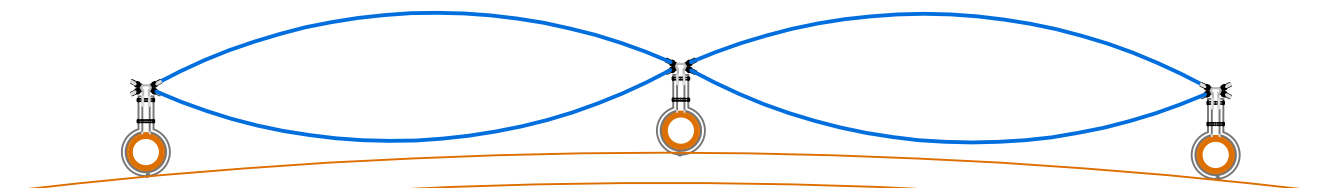


Figure 14.4o: Section 1:10

OPTION 4

By overlapping the panels only in one direction, water will seep into the structure because it is difficult to overlap adjacent panels (figure 14.4r.ii). Hence taking inspiration from roman clay tiles used for roofing (figure 14.4q), alternate panels are inverted (figure 14.4r.iii). Water flows from convex panels to concave panels which forms a channel for the water to flow. At the valley point, the direction of the panels are changed, in order to allow water to flow out from the roof (figure 14.4p). With this cladding system, where glass is single curved and overlapped in both the directions, it is possible to protect the structure from rains.

- ✓ WATER PROOF
- ✓ TOLERANCE
- ✗ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

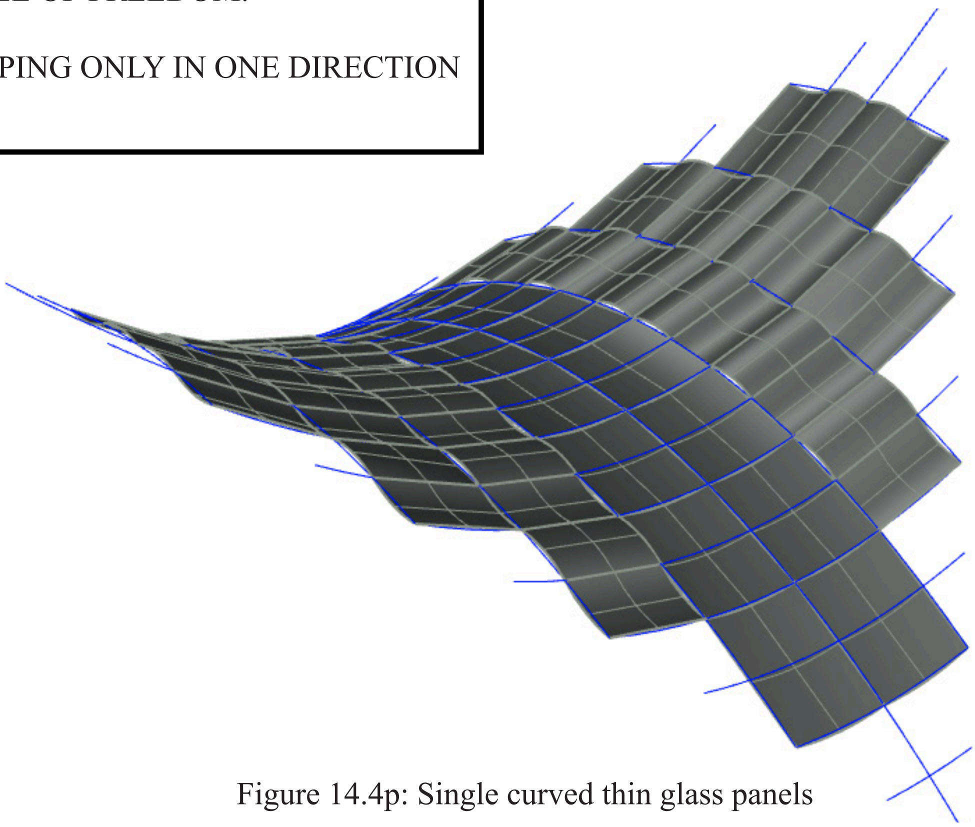
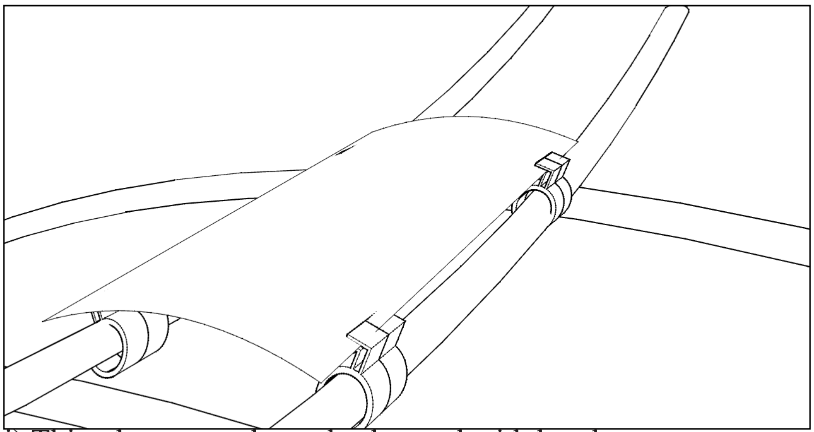
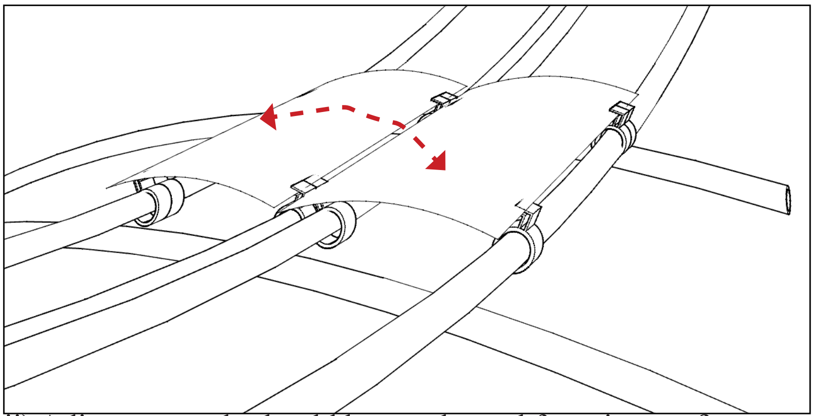


Figure 14.4p: Single curved thin glass panels

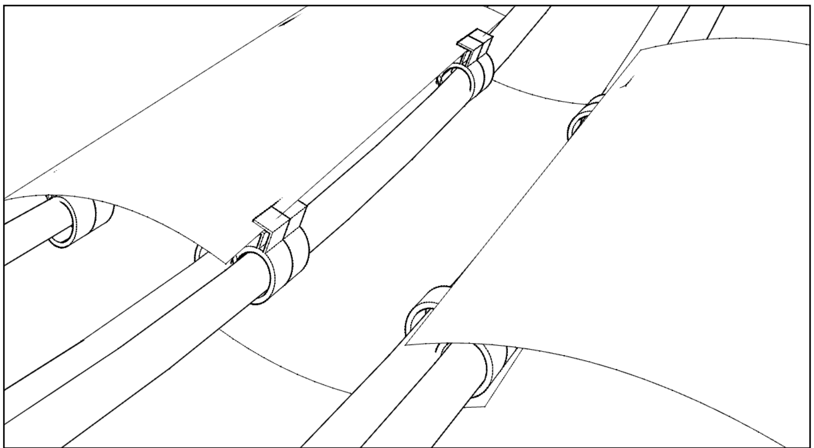
Figure 14.4q: Roman clay roofing tiles.



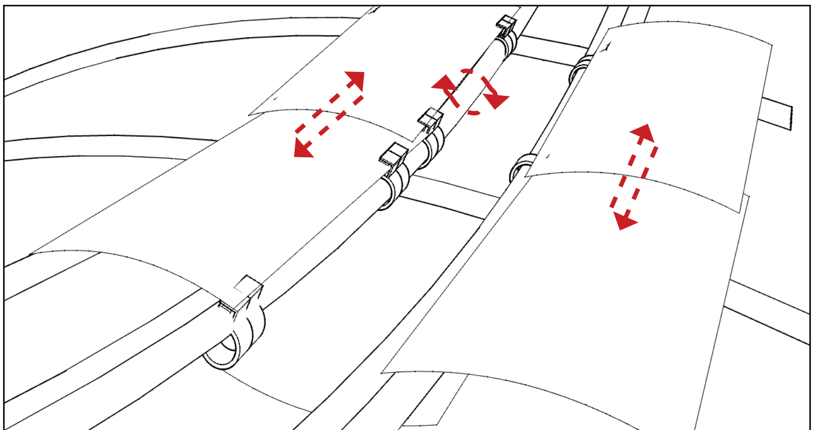
i) Thin glass curved panels clamped with bamboo.



ii) Adjacent panels should be overlapped for rain proofing.



iii) Alternate panels inverted for overlapping.



iv) Panels overlapped in both directions.

Figure 14.4r: Panel orientation and overlapping

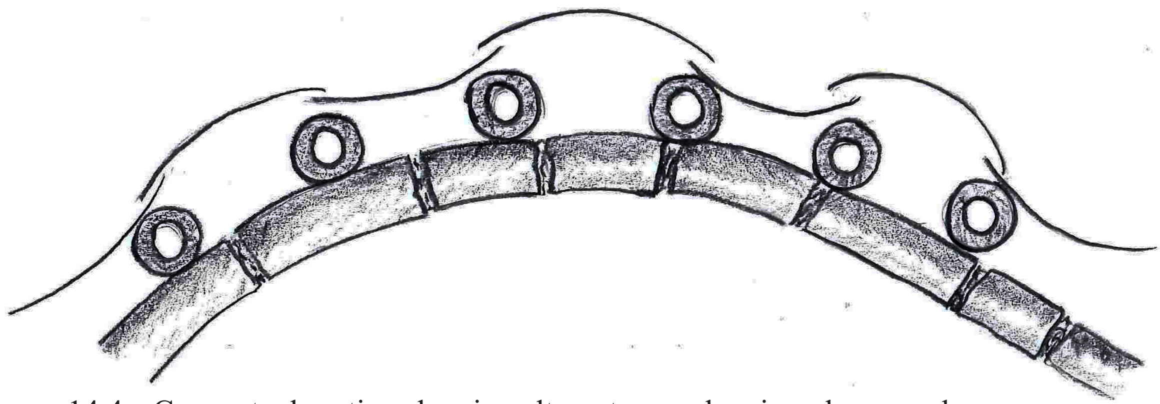


Figure 14.4s: Conceptual section showing alternate, overlapping glass panels

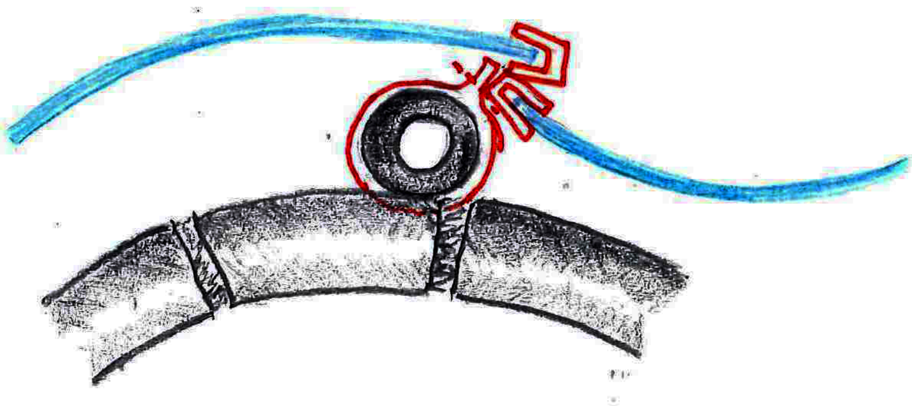


Figure 14.4t: Both glass and bamboo clamped and connected to each other.

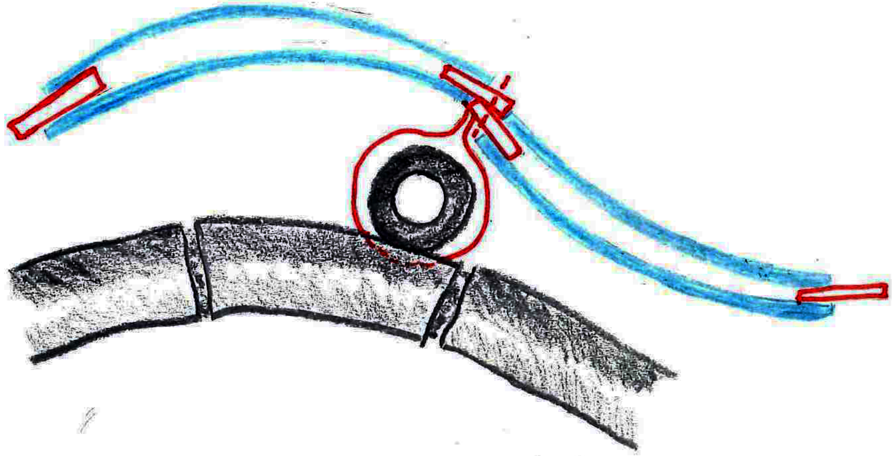


Figure 14.4u: Metal laminated between two layers of thin glass and then connected to clamp

Figure 14.4s, shows basic section of glass panels positioned as per the curvature of the bamboo, in turn the curvature of the roof structure. Alternate panels are inverted and overlap with convex panels. The panels will be clamped together in order to maintain the curvature. Bamboo is also clamped to avoid bolting which causes splitting (figure 14.4t). Both the bamboo and glass clamps are then bolted together. Glass is not bolted to fix the clamps to the glass, in order to prevent local stresses. Glass is reinforced with metal laminated in between the two layers and this metal is then connected to the clamp (figure 14.4u).

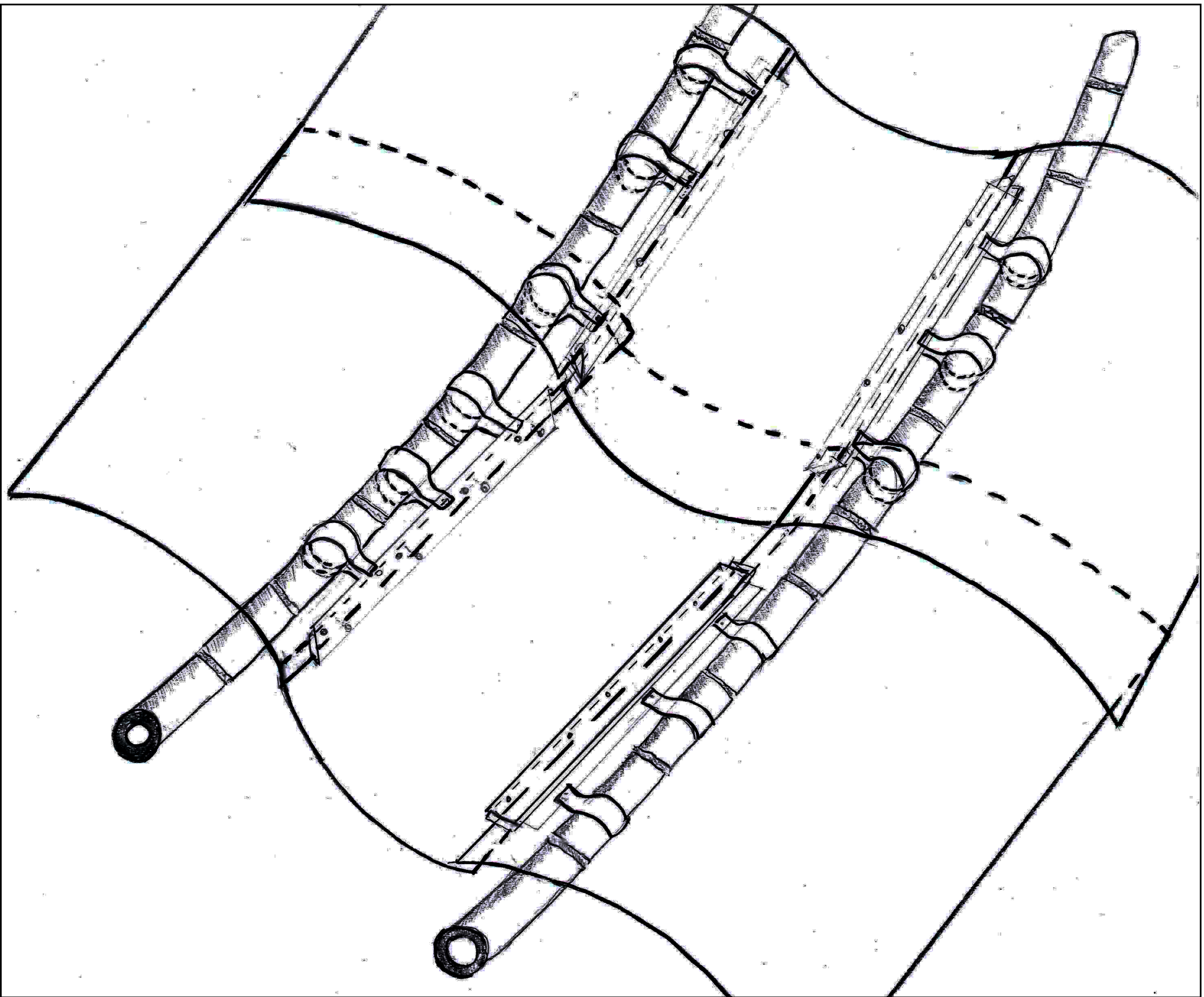


Figure 14.4v: Single curved thin glass panels overlapping each other and clamped to bamboo.

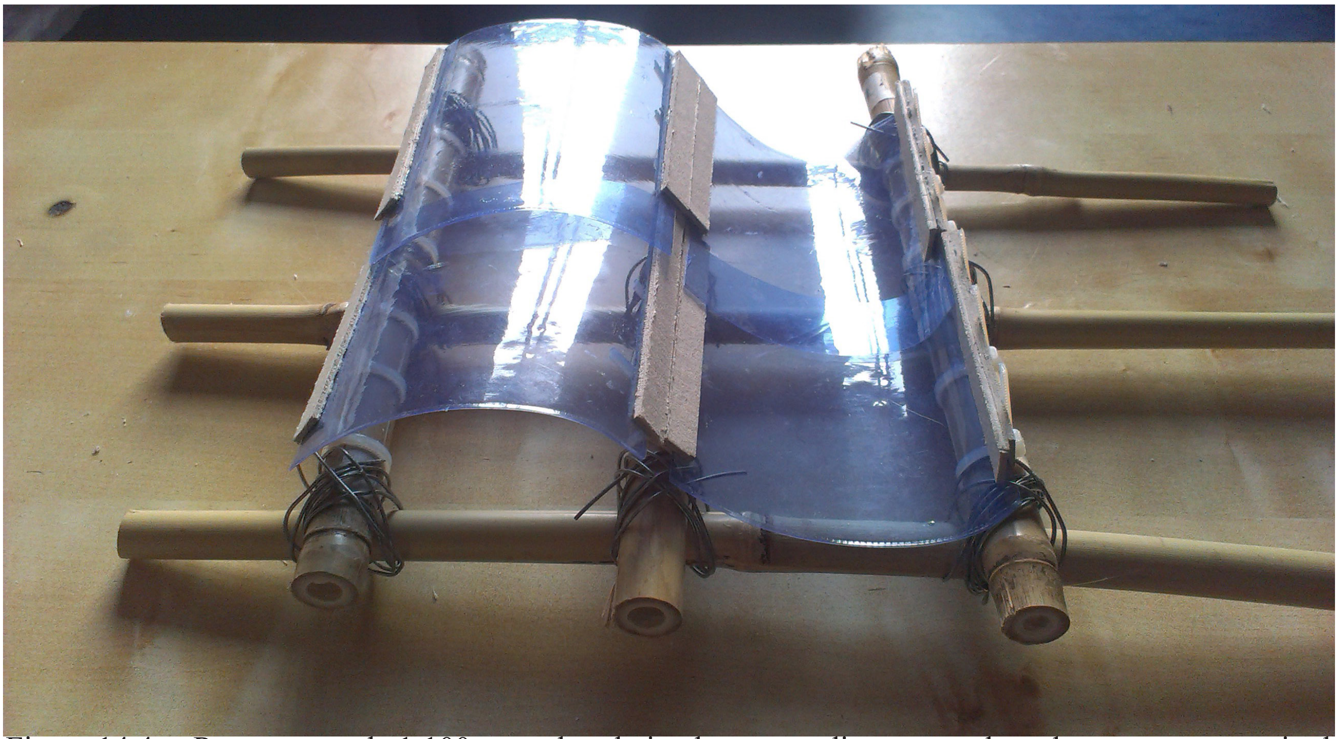


Figure 14.4w: Prototype scale 1:100 to study relation between adjacent panels and movements required while fixing.

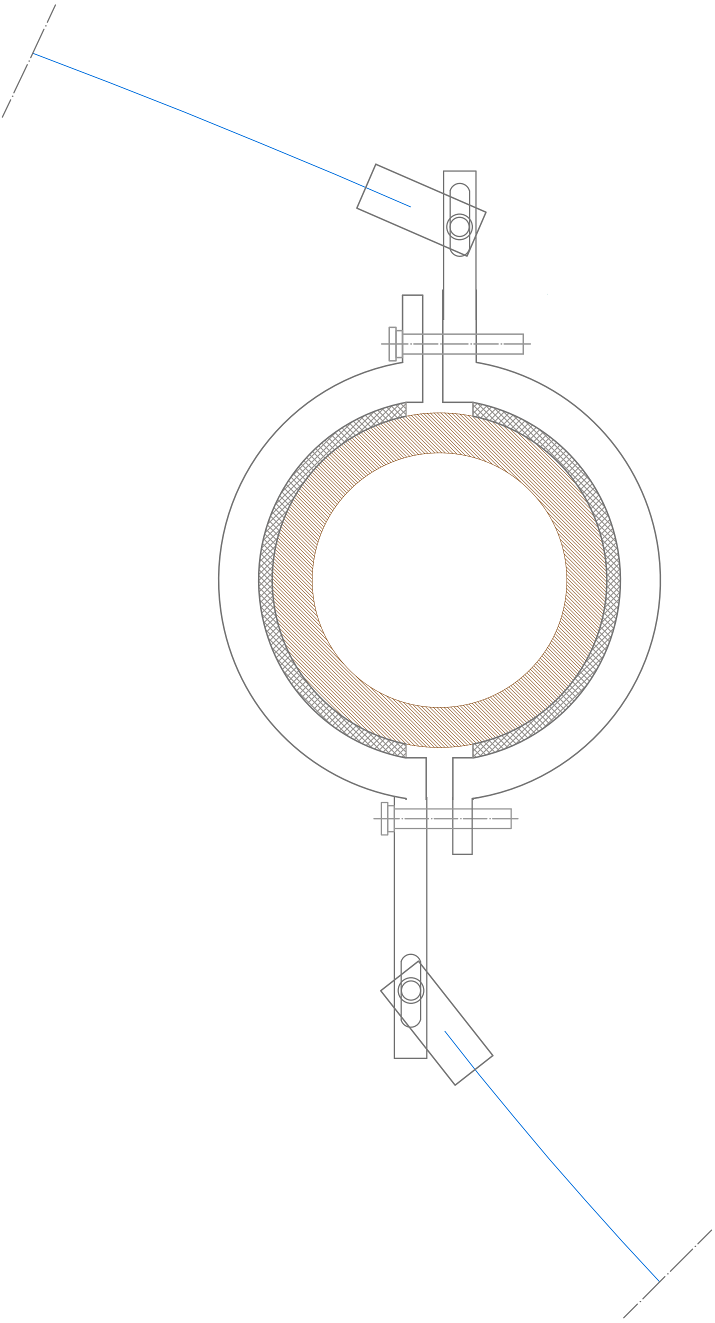


Figure 14.4x: Glass clamps attached on opposite sides of bamboo.

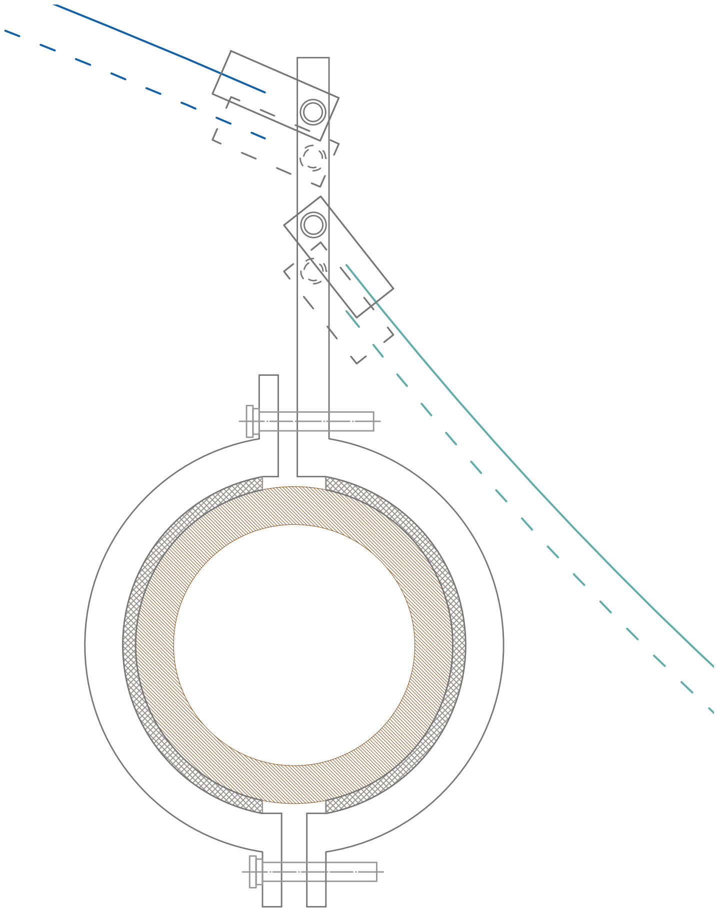


Figure 14.4y: Bamboo clamp extended as vertical plate to attach glass clamp. As bamboo is bent the glass clamps will attach at different levels.

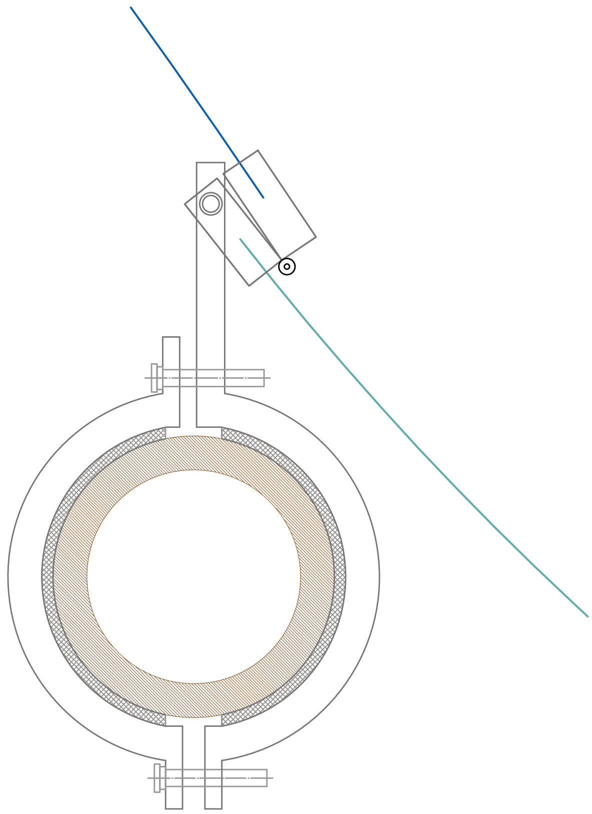


Figure 14.4z: Glass clamps hinged together to create greater overlap between two panels.

14.5 ASYMMETRIC CYLINDRICAL CURVATURE

After exploring all the possibilities, it was difficult to have two separate clamps for adjacent panels. When allowing panels to independently rotate, the joint between the clamps is not water tight and many components are required. Hence a single component is used for fixing two adjacent glass panels. With this kind of configuration, the glass panels are no more symmetrically curved. In order to adjust with grid distance, it well stretch or bend. But the angle at which the panels are fixed is the same. This leads to asymmetrical curvature. With single piece for clamping two glasses, the water tight issue is solved.

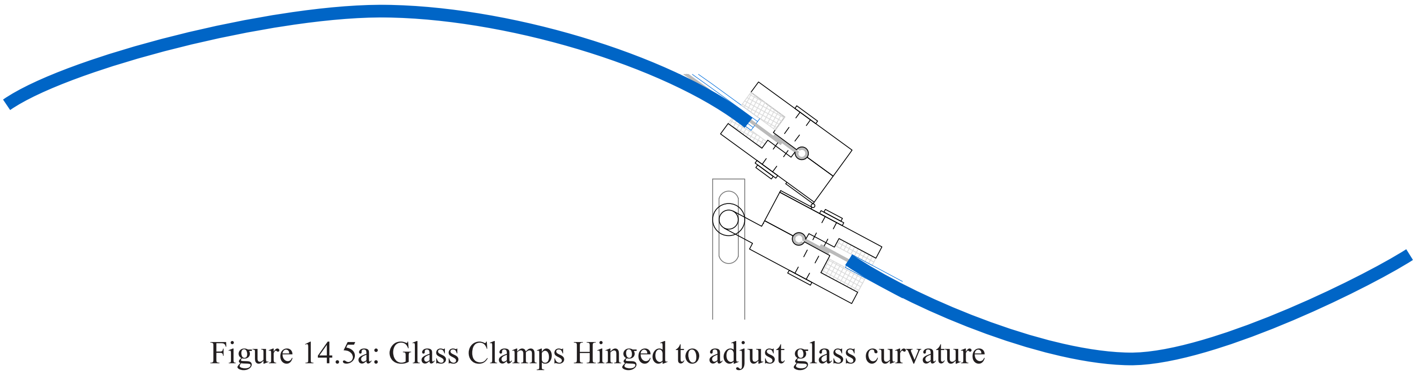


Figure 14.5a: Glass Clamps Hinged to adjust glass curvature

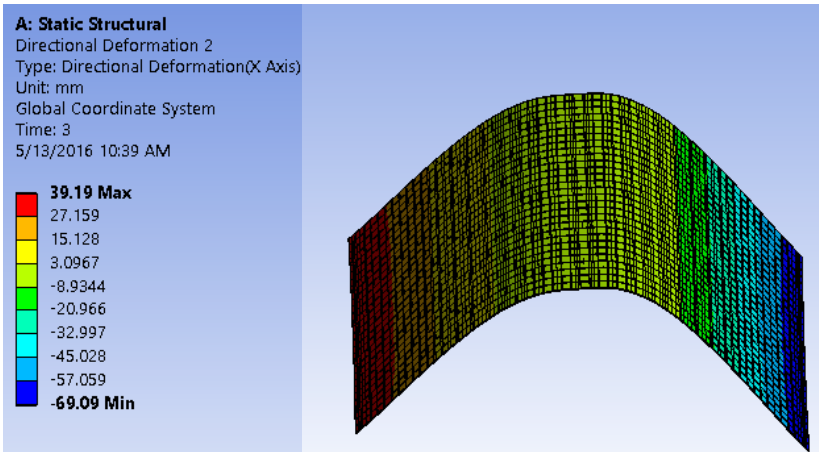


Figure 14.5b: Δx = 39.19MM
Δx = -69.09MM

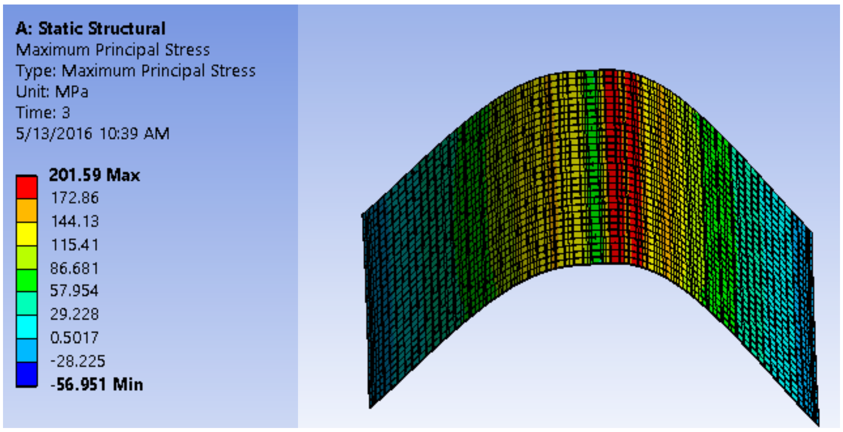


Figure 14.5c: σmax = 201.50 MPa

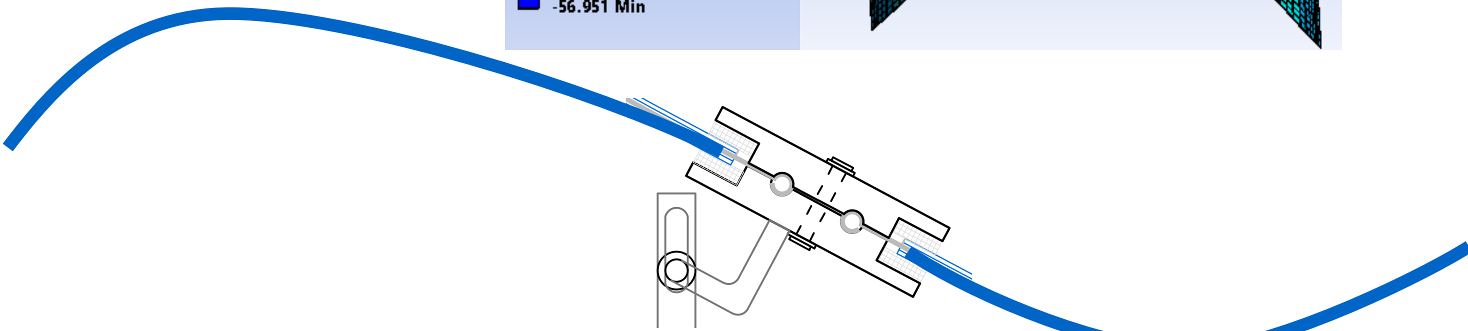


Figure 14.5d: Glass Clamps fixed, glass curvature asymmetrical

14.6 CONNECTION DETAIL

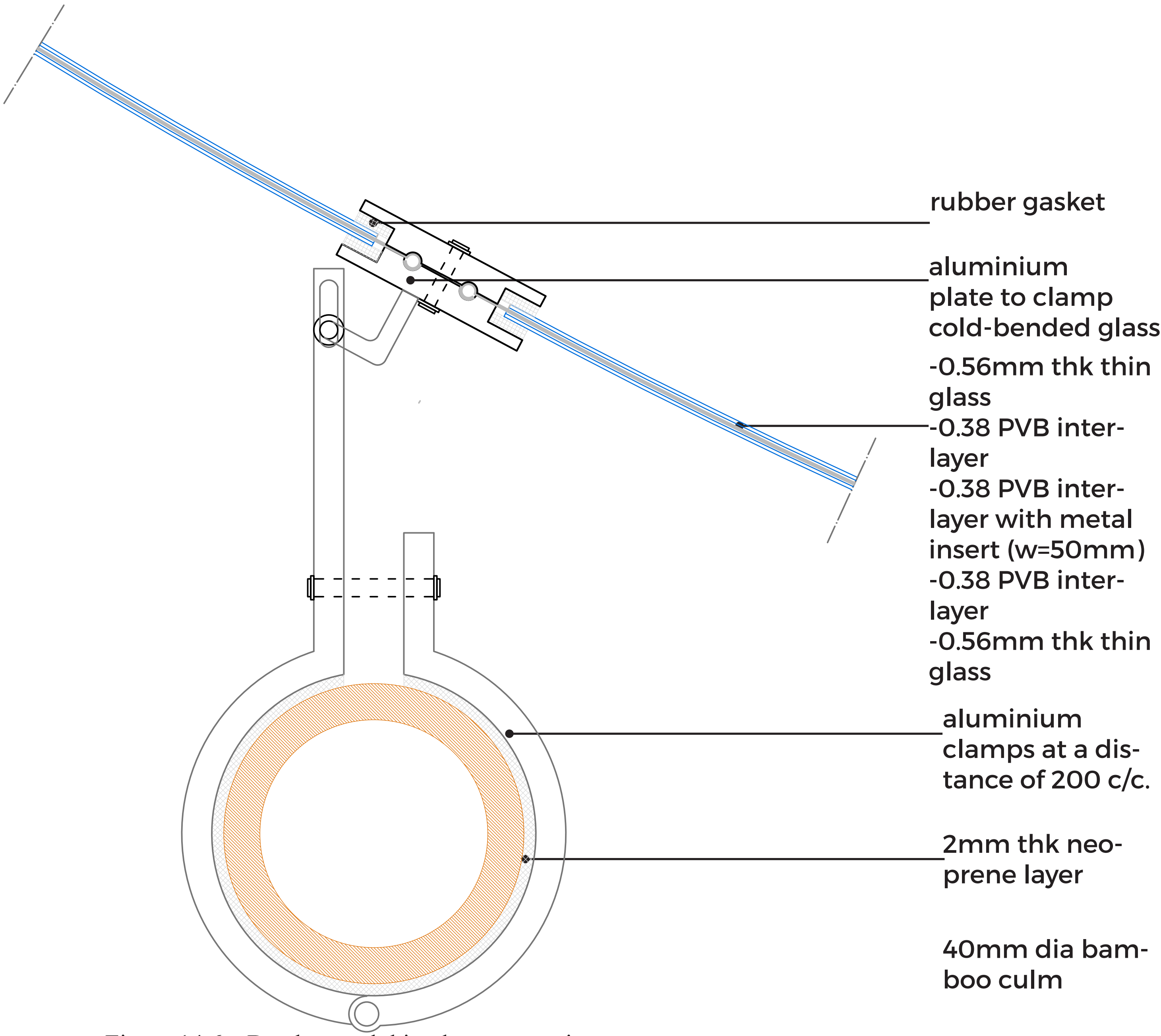


Figure 14.6a: Bamboo and thin glass connection
scale 2:1

OPTION 5 = (1+4)

In the previous option, the glass clamps were still allowed to rotate according to the curvature of the glass. But the connection between the bamboo clamp and glass clamp was not feasible (Figure 14.6a). Hence going back to option1, where the all the panels were curved in one direction. In this option, the glass clamps is a single component to connect two glass panels. The glass clamps cannot rotate. As a result, the panels will adjust to the main structural grid by asymmetric bending. Both the glasses will come out from the clamps at the same angle but may not have the same curvature. Waterproof is achieved on both sides (Figure 14.6e).

- ✓ WATER PROOF
- ✓ TOLERANCE
- ✓ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

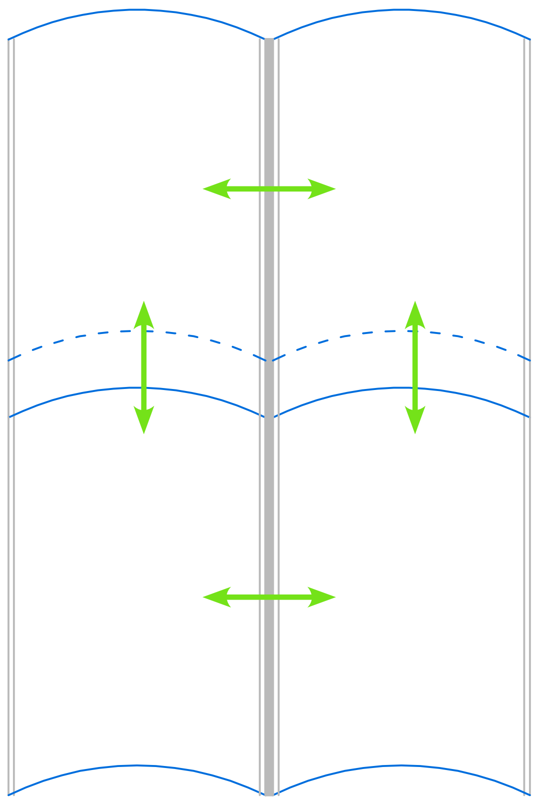


Figure 14.6b: Waterproofing on both direction, one side glass overlap, other side water tight mechanical fixture.

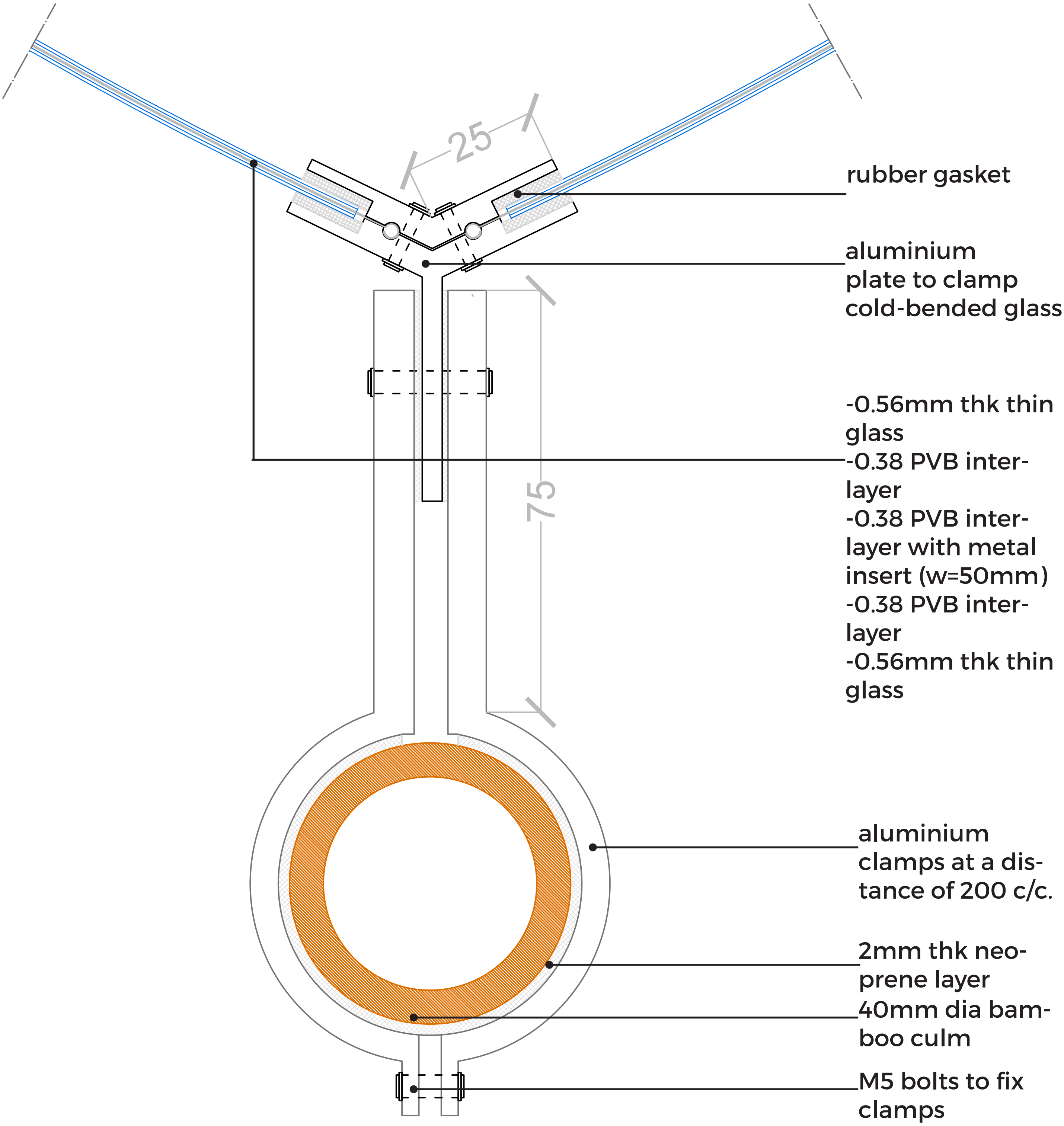


Figure 14.6c: Detail 1:1- Both glass clamps form one single component.

14.6 ASSEMBLY SEQUENCE

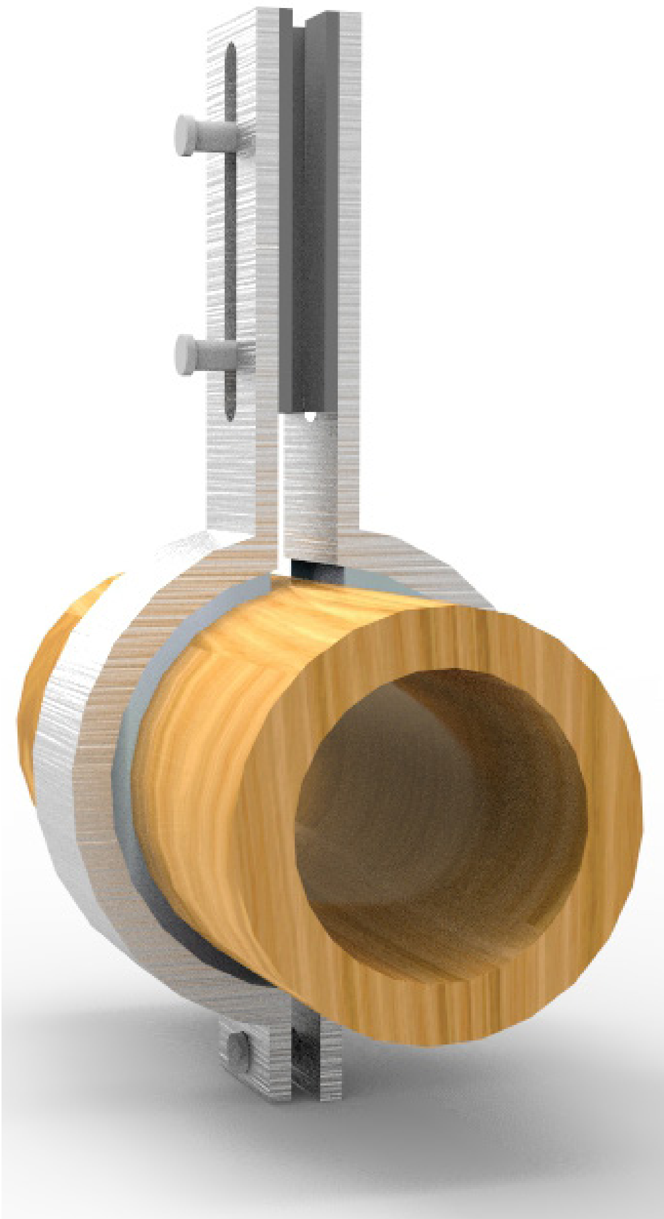


Figure 14.6b: Aluminium clamps fixed to bamboo

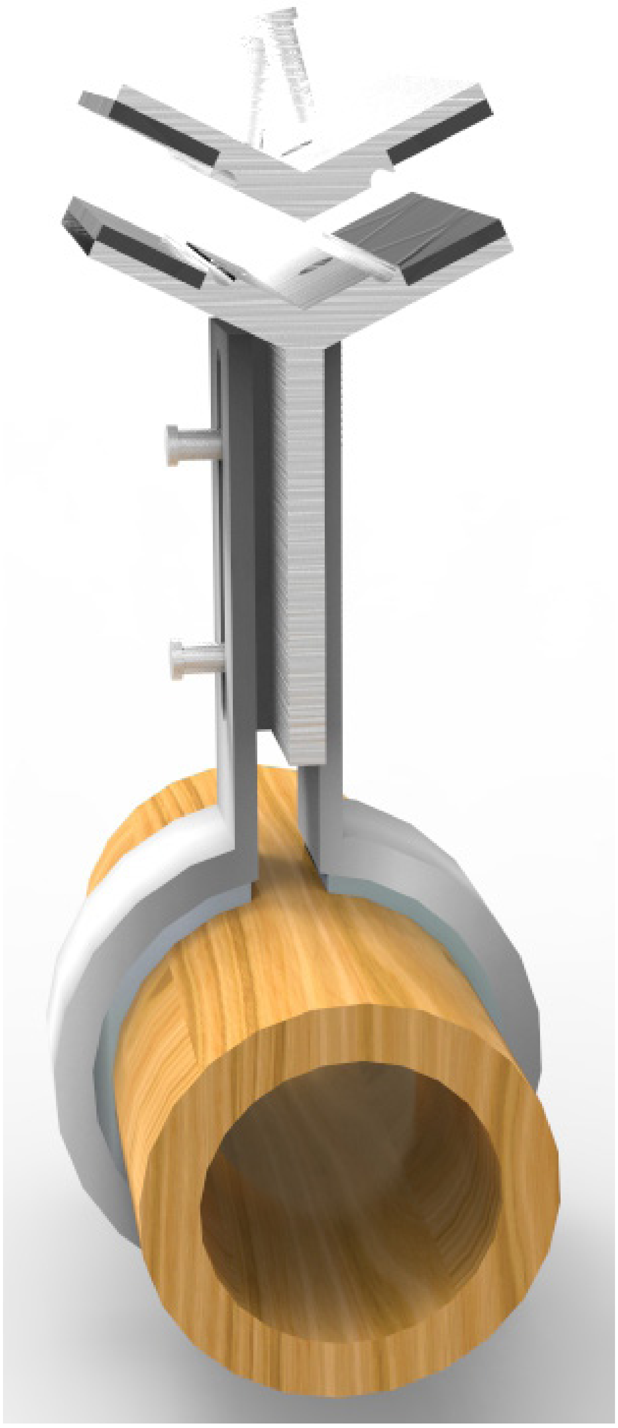


Figure 14.6c: Connecting glass clamps to bamboo clamps.

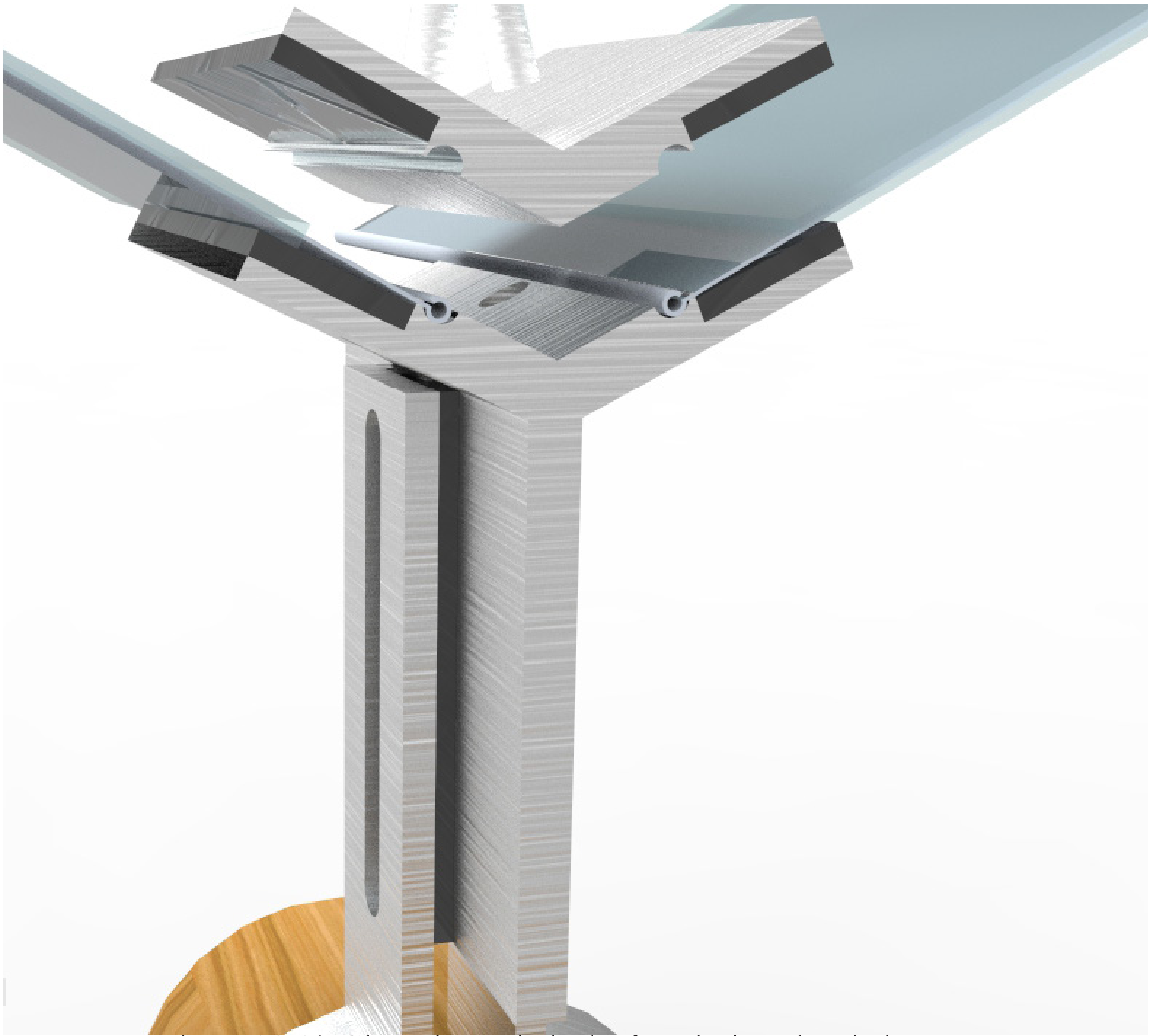


Figure 14.6d: Glass clamps bolted, after placing glass in between.

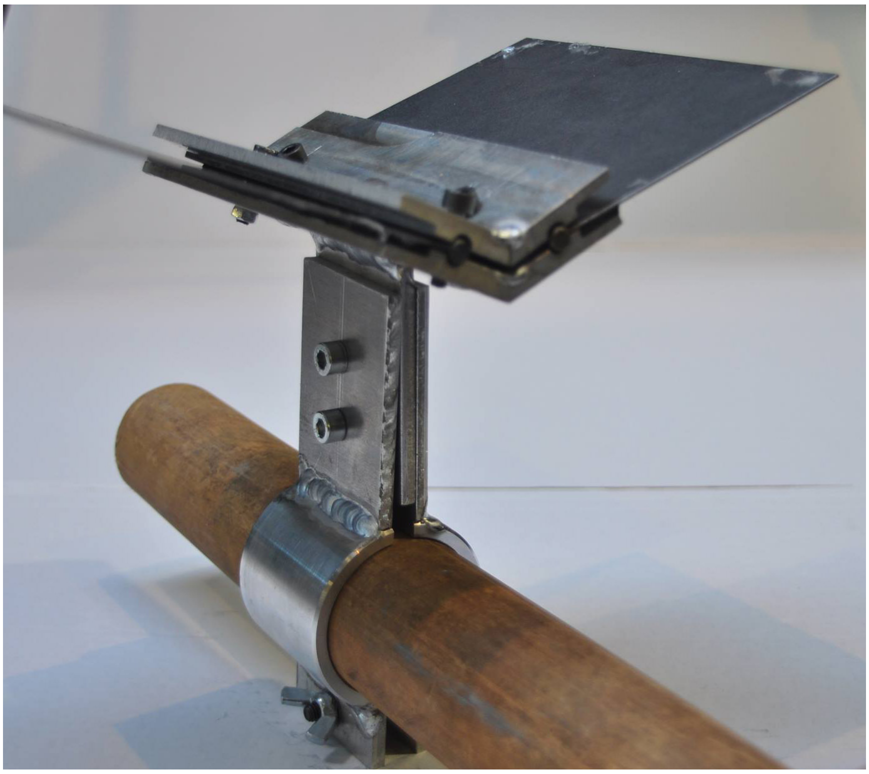
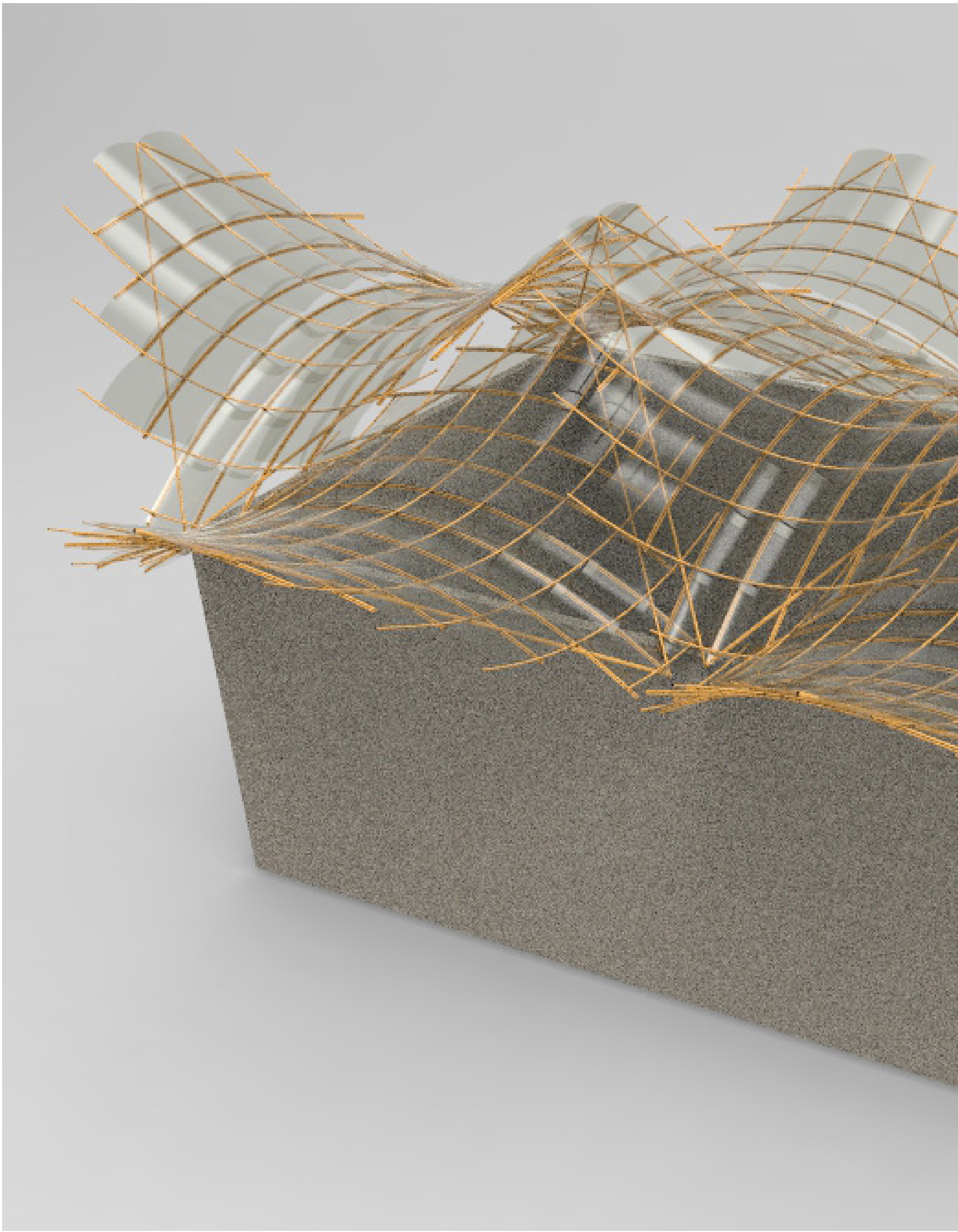
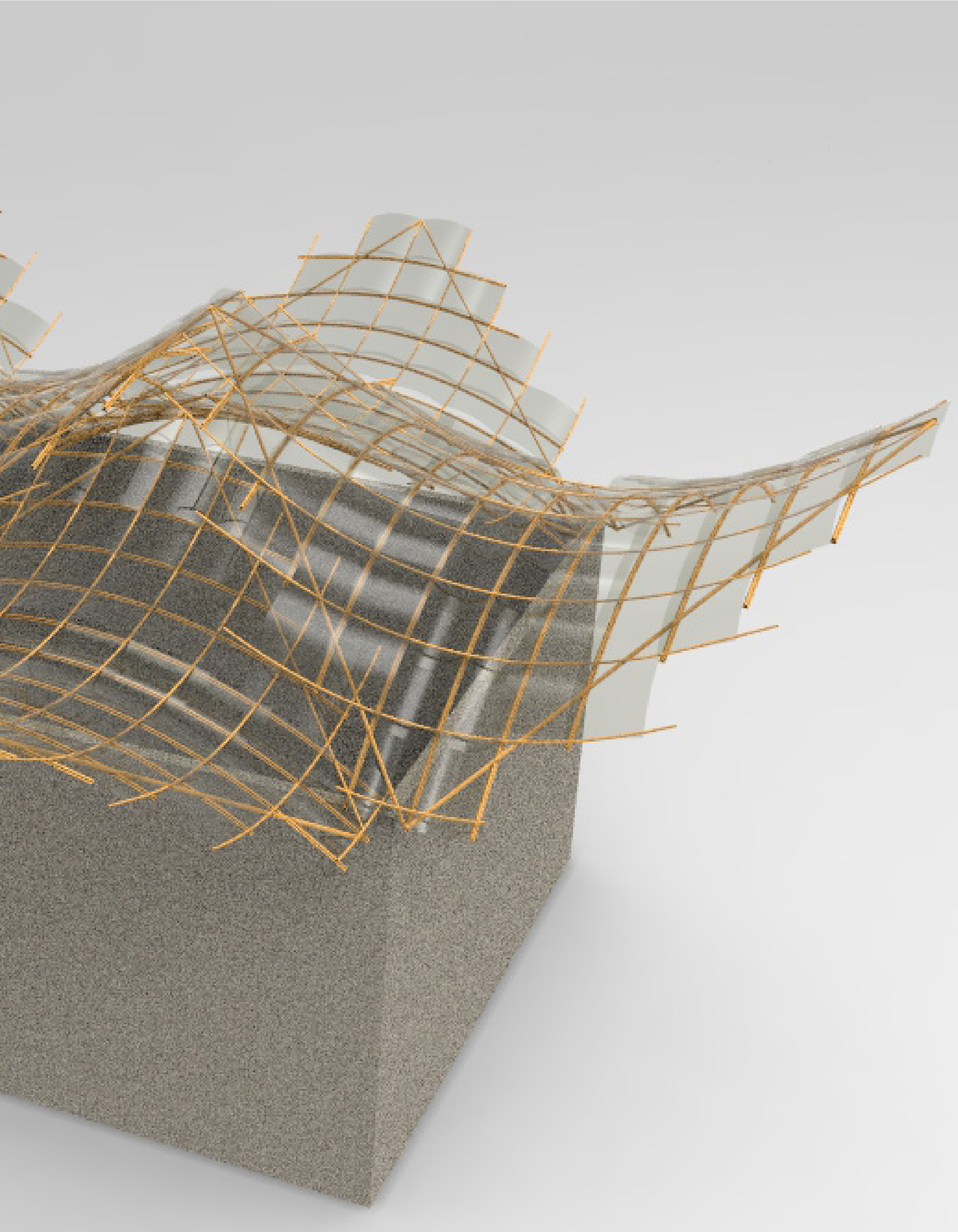


Figure 14.6e: Bamboo and thin glass connection prototype 1:1





OPTION 5 = (1+4)

The clamps attached to bamboo have a layer of rubber gasket to increase friction between bamboo and aluminium clamps. This is important so that the clamps do not rotate because of horizontal wind force. If the clamps rotate, they will need to be fixed in position by bracing with other clamps. To know resistance the clamps offer against the wind force, the joint is evaluated in the next section. However to achieve maximum resistance it should be ensured that the clamps are tightly bolted and fixed to bamboo. The diameter of the bamboo may differ plus or minus 1cm. Hence extra layer of rubber gasket needs to be added before clamping.

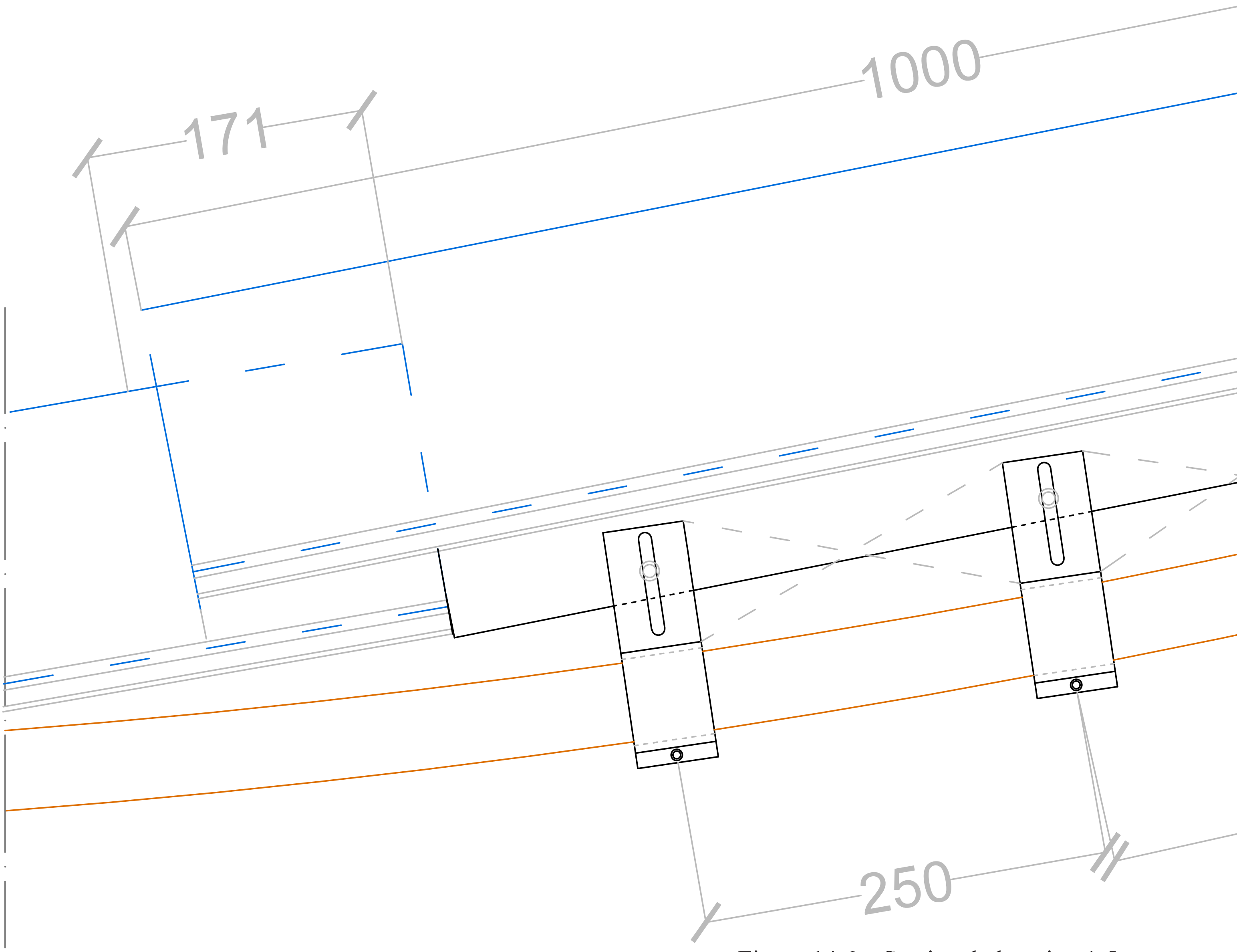
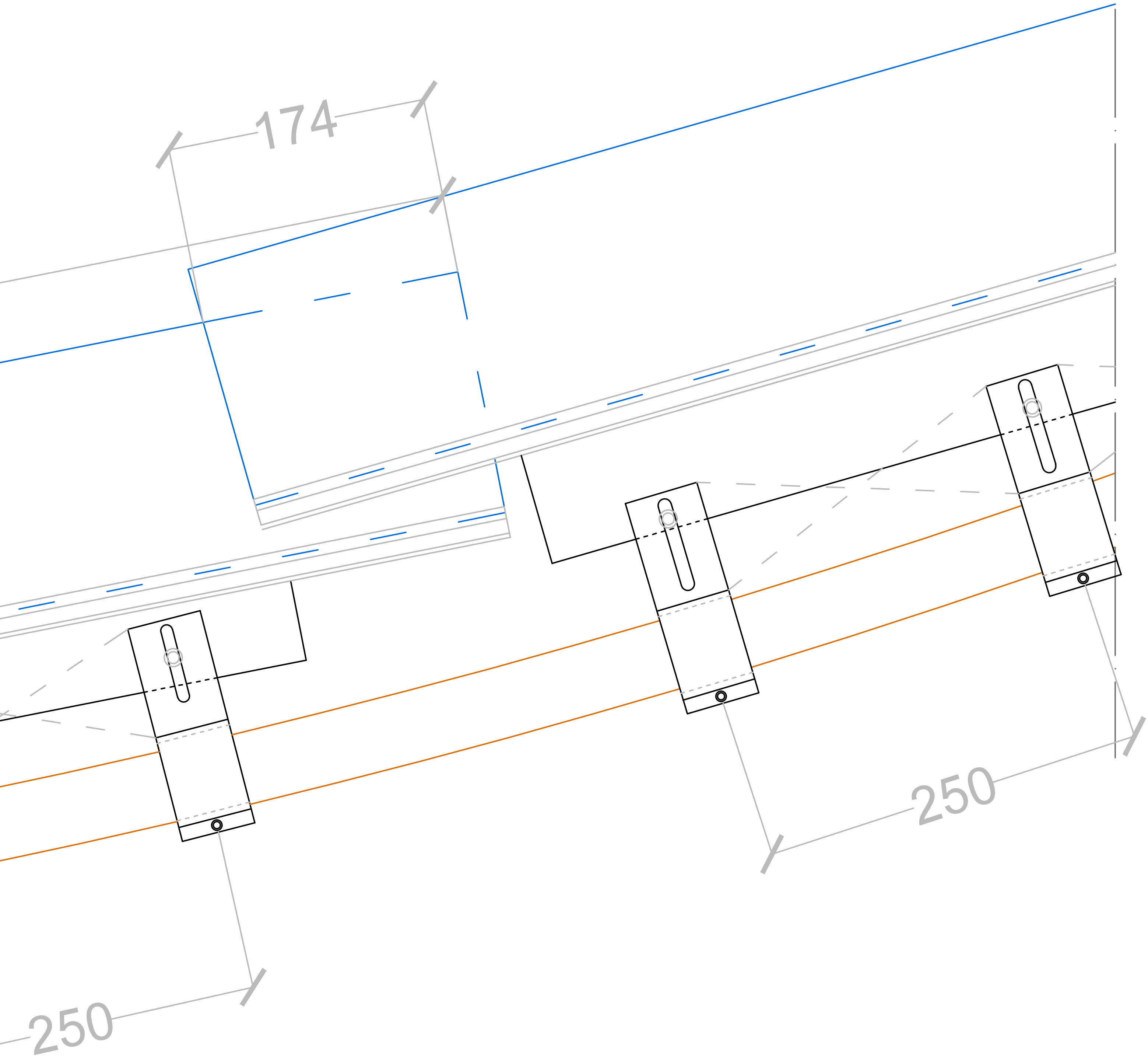


Figure 14.6g: Sectional elevation 1:5


174
250
250

14.7 JOINT EVALUATION

The extension of the clamps fixed to the bamboo rotate around the axis of the bamboo. Hence to secure it on the uneven surface of the bamboo, a layer of silicon is needed between the aluminium clamp and bamboo surface. This will provide additional fiction preventing it to rotate. The possibility of the clamp rotating is because of wind acting on the clamp. This will be the applied moment. And the resisting moment is due to the fiction between the rubber-bamboo and because of the clamping force. Basic values have been assumed and the joint is evaluated. For the clamp to restrict rotation, the resisting moment has to be greater than applied moment.

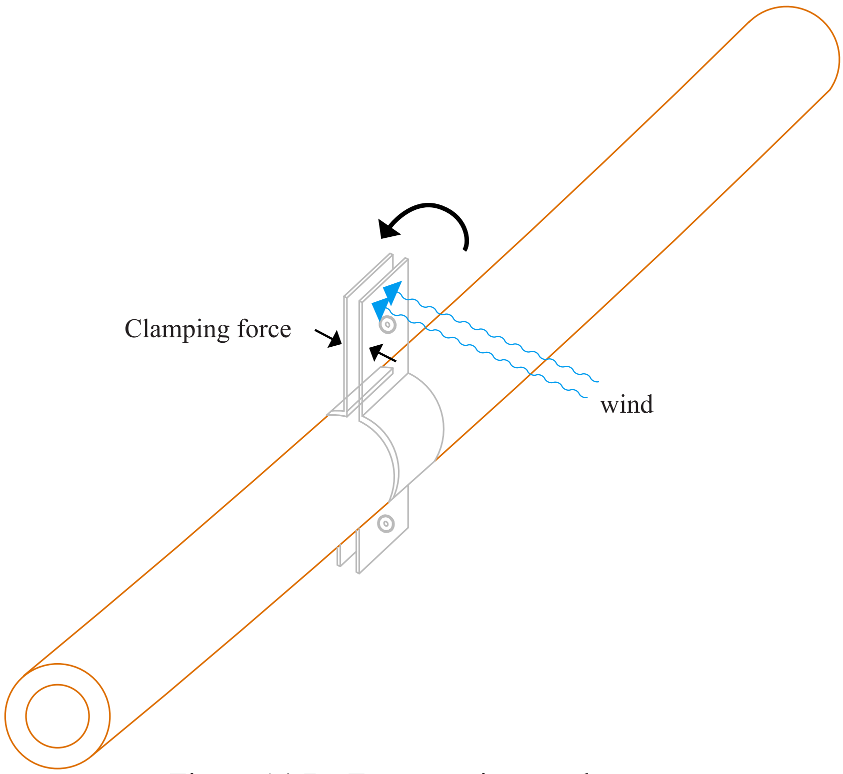


Figure 14.7a: Forces acting on clamps

torque $\tau = F.R.\sin\theta$

where,
F - Applied force (N)
R - Distance between the central axis and force applied.
θ - Angle at which force is hitting the object.

Applied moment		Resisting moment
wind torque $\tau_w = F_w.R$	<	frictional torque $\tau_f = F_c.R.\mu$
0.6 N.m		63.36 N.m

	CLAMPING FORCE kN			
	PROPERTY CLASS			
	8.8/8	9.8/9	10.9/10	12.9/12
M3	2.2	-	3.1	3.7
M4	3.8	-	5.5	6.4
M5	6.2	6.9	8.9	10.4
M6	8.7	9.8	12.5	14.6
M8	15.9	17.8	22.8	26.6
M10	25.3	28.3	36.1	42.2
M12	36.7	41.1	52.5	61.4
M14	50	56.1	71.6	84
M16	68.2	76.5	97.5	114
M18	86.2	-	119	140
M20	110	-	152	178
M22	136	-	189	220
M24	159	-	220	256

Figure: 14.7b: Clamping force of bots Fc
ref: https://www.anochrome.com/technical/torque-tension/

MATERIALS	STATIC FRICTION	KINETIC FRICTION
Rubber on dry ice	1.0	0.7
Rubber on wet concrete	0.7	0.5
Wood on wood	0.5	0.3
Waxed wood on wet snow	0.14	0.1
Metal on wood	0.5	0.3
Steel on steel (dry)	0.6	0.3
Steel on steel (oiled)	0.05	0.03
Teflon on steel	0.04	0.04
Bone lubricated with synovial fluid	0.016	0.015
Shoes on wood	0.9	0.7
Shoes on ice	0.1	0.05
Ice on ice	0.1	0.03
Steel on ice	0.4	0.02

Figure 14.7c: Friction coefficient
ref: http://www.slideshare.net/ElviIdiosolo/friction-4004954

In the earlier case the applied moment was considered only due to the wind force. Thin glass panels, which are cold bent have high rection forces. But the adjacent panels at the center negate the reaction forces. Only panels at the edges will transfer these forces to the clamp. Hence the applied moment will be a combination of wind force and reaction force of the glass. For the clamp to not rotate the resisting moment should be greater than the total resisting moment. Using FEM, reaction forces of bent glass was determined (Figure 14.7f)

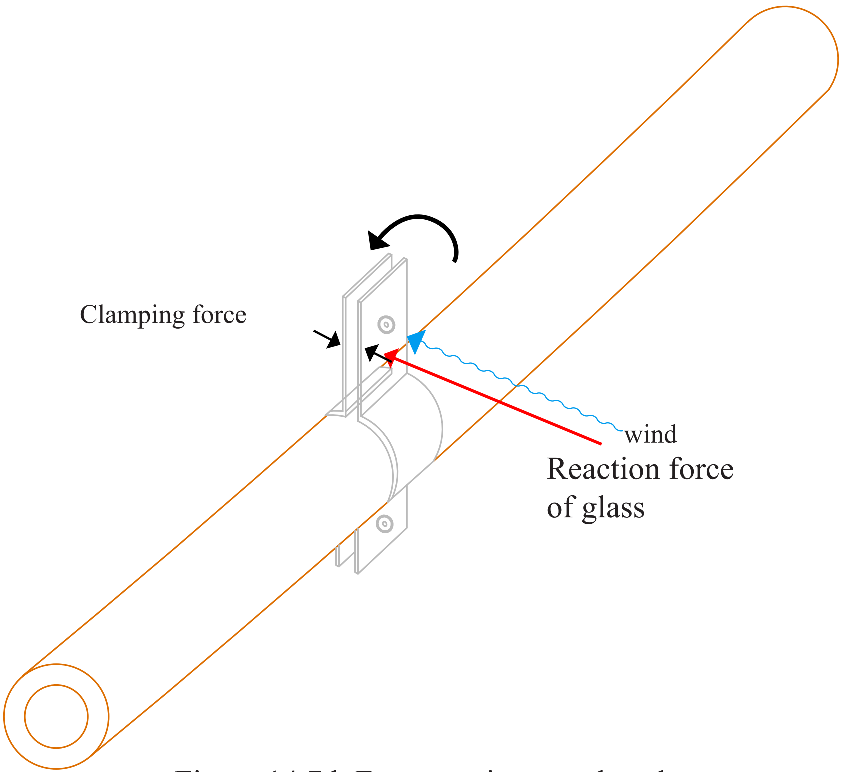


Figure 14.7d: Forces acting on edge clamps

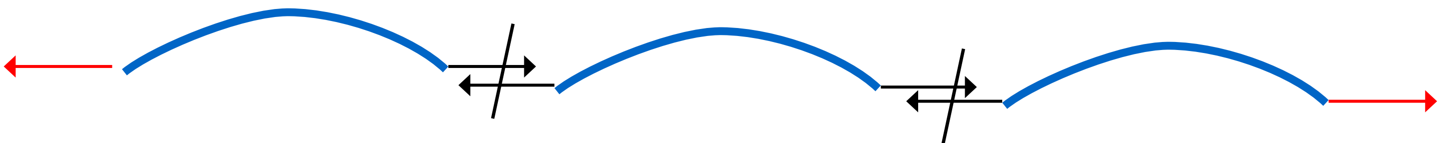


Figure 14.7e: Reaction force of last panel is considered. Reaction forces of in between panels will negate each other.

Applied moment		Resisting moment
wind torque τ_w + glass torque $\tau_g = [F_w + (F_g/3)].R$		frictional torque $\tau_f = F_c.R.\mu$
36.26 N.m	$<$	63.36 N.m

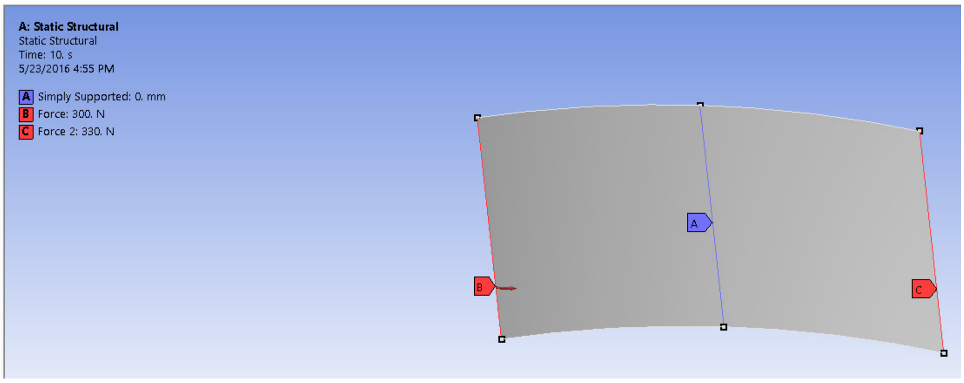


Figure 14.7f: Boundary conditions to determine reaction forces

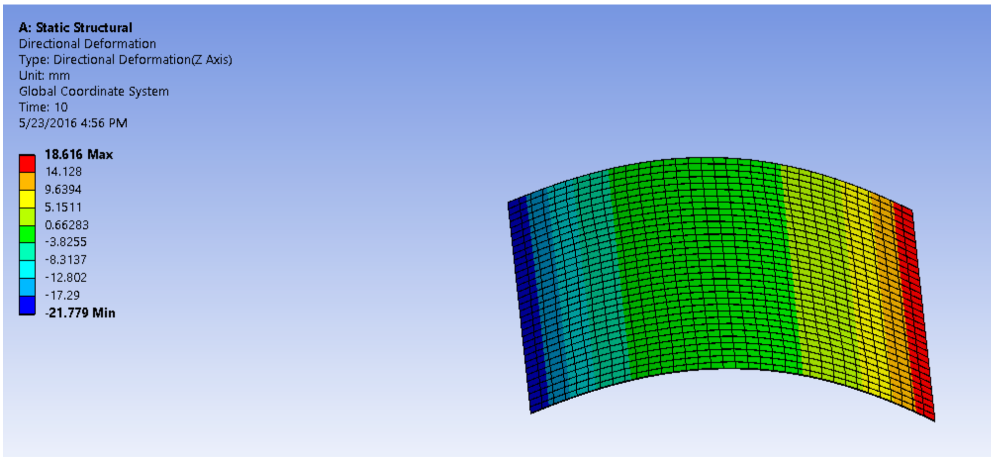


Figure 14.7g: Deflection $\Delta x = 39.19MM$ $\Delta x = -69.09MM$

14.8 SECONDARY CONNECTIONS

Apart from bamboo and glass connection, other end connections are also critical. Hence a basic concept and detail of bamboo to concrete and shell to shell connection is dicussed in this section. These connections should also help in maintaining the structure durable. As a result metal connections, which are more reliable are used.

The hyperbolic roof structure sits on the RCC beam. Only part of the roof structure is touching the beam and the rest in cantilivered. The main element of the roof is the middle arch which takes the forces in compression and transfers it to the base. The side arms also sit on this concrete structure and takes the forces in tension. Various tensile connections have been explored and researched by bamboo engineers. Bamboo to concrete connection is detailed by referring to connection done by San Val architects for vertical bamboo housing in Haiti (Figure 14.8b) and another connection detail seen in (Figure 14.8c). Figure 14.8b shows that the end of the bamboo is split in order to taper it. The tapering of bamboo is secured by using aluminium ring. This tapered bamboo is then inserted into a metal shoe which is connected to a base plate (Figure 14.8c).

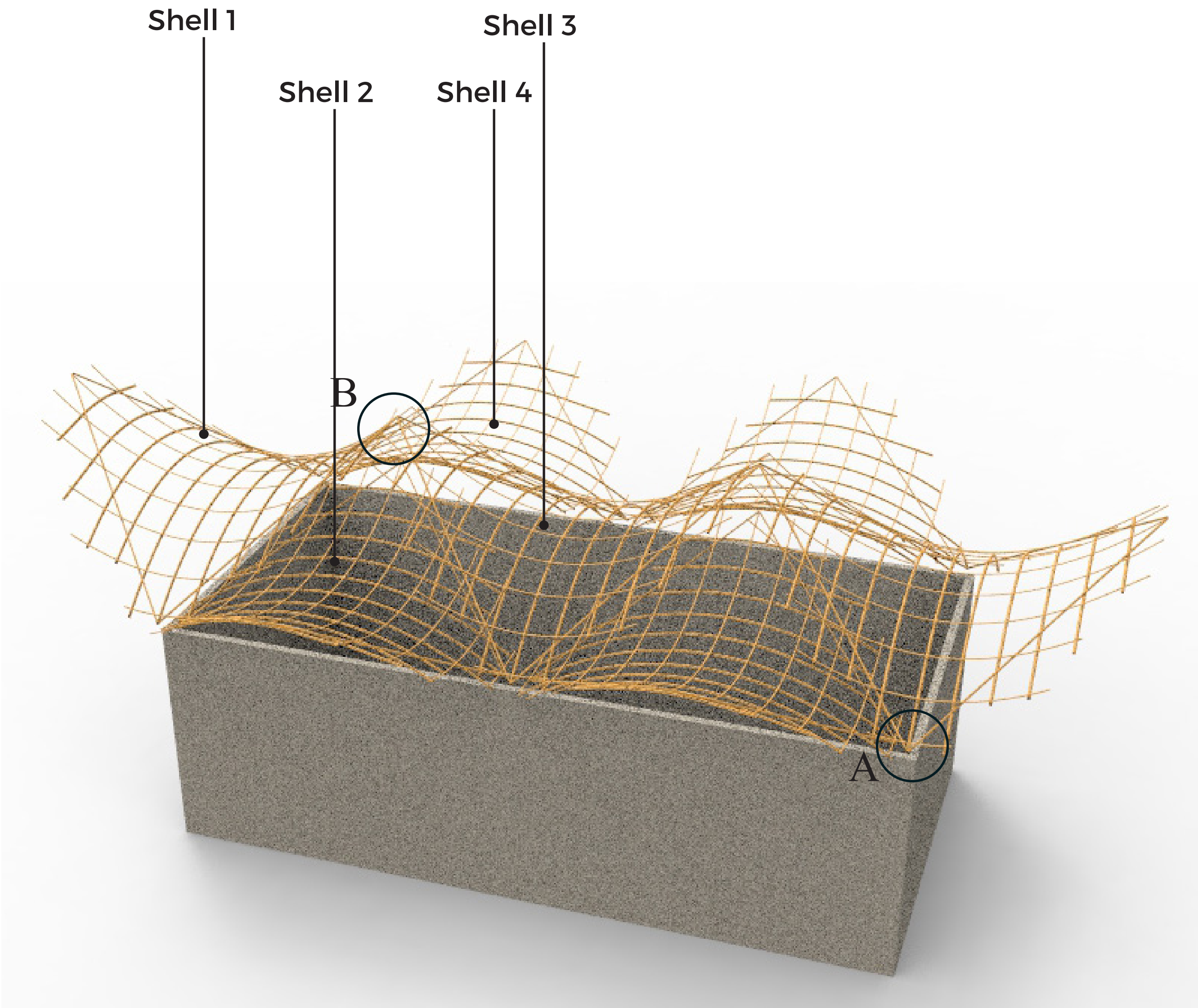


Figure 14.8a

Figure 14.8b: Bamboo sliced and tapered using aluminium ring (Val, 2011).

Figure 14.8c: Bamboo end connection. ref: (unknown)

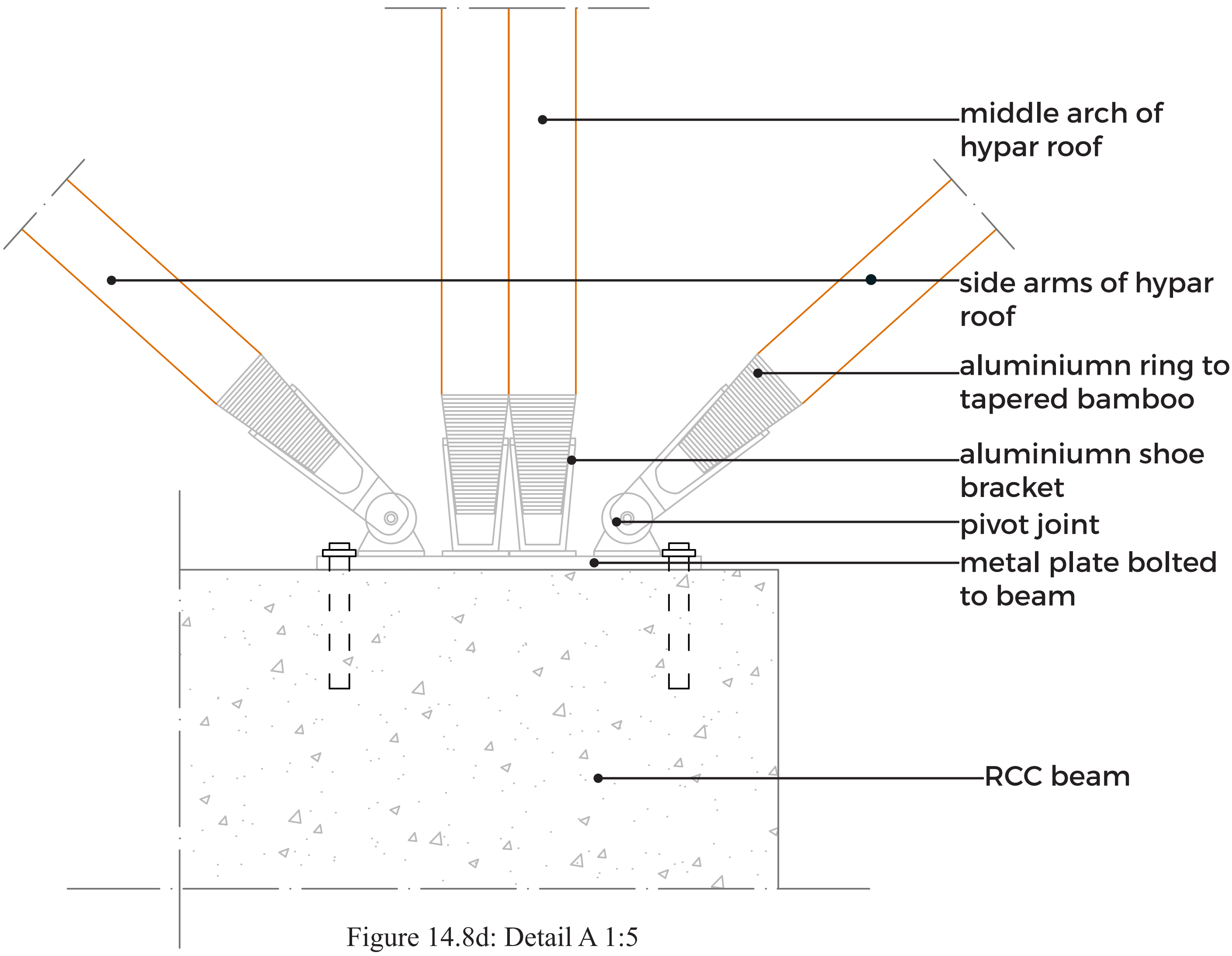
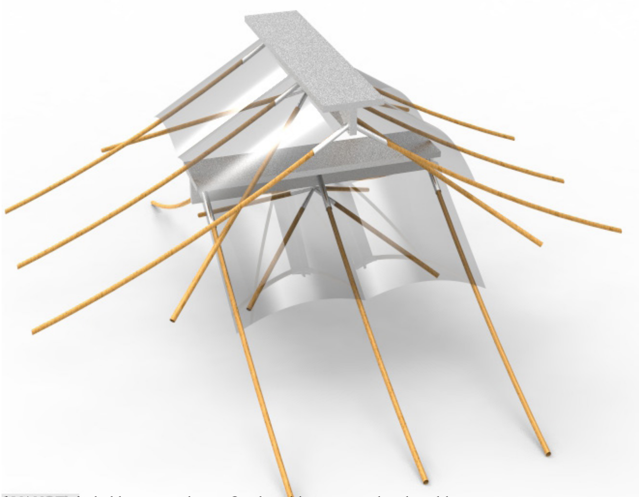


Figure 14.8d: Detail A 1:5

i) Side arms of shell 2 and shell 4

ii) Middle arch of shell 2 and shell 4

iii) Side arms of shell 1 and shell 3



iv) Middle arch of shell 1 and shell 3

Figure 14.8e: shell to shell apex connection sequence

As seen in figure 14.8a, the roof is made up of seven hypar gridshells. At the cantilivering edge the shells are connected to each other. Four hypar shells are connected to each other at lower level and three hypar shells are connected at higher level. The side arms and three concave parabolic arches of layer 6 (Figure 14.8e and Figure 15.1e) are connected to the adjacent hypar shell. The connection is similar to detail A (Figure 14.8d). Two side arms of each shell 2 and 4are connected at lowest level (Figure 14.8e.i). The side arms are connected together forming x-joints (Figure 14.8g). Bamboo for this connection is also tapered (Figure 14.8b). The three concave parabolic arches of each shell are connected using a tensile pivot joint (Figure 14.8f). This is connected to a T-section so that the water flows to the curved glass panels (Figure 14.8e.ii).
Bamboo to bamboo connection in the grid can be developed using aluminium clamps (Figure 14.8h). Futher investigation is needed to check the strength and feasibility of these joints.

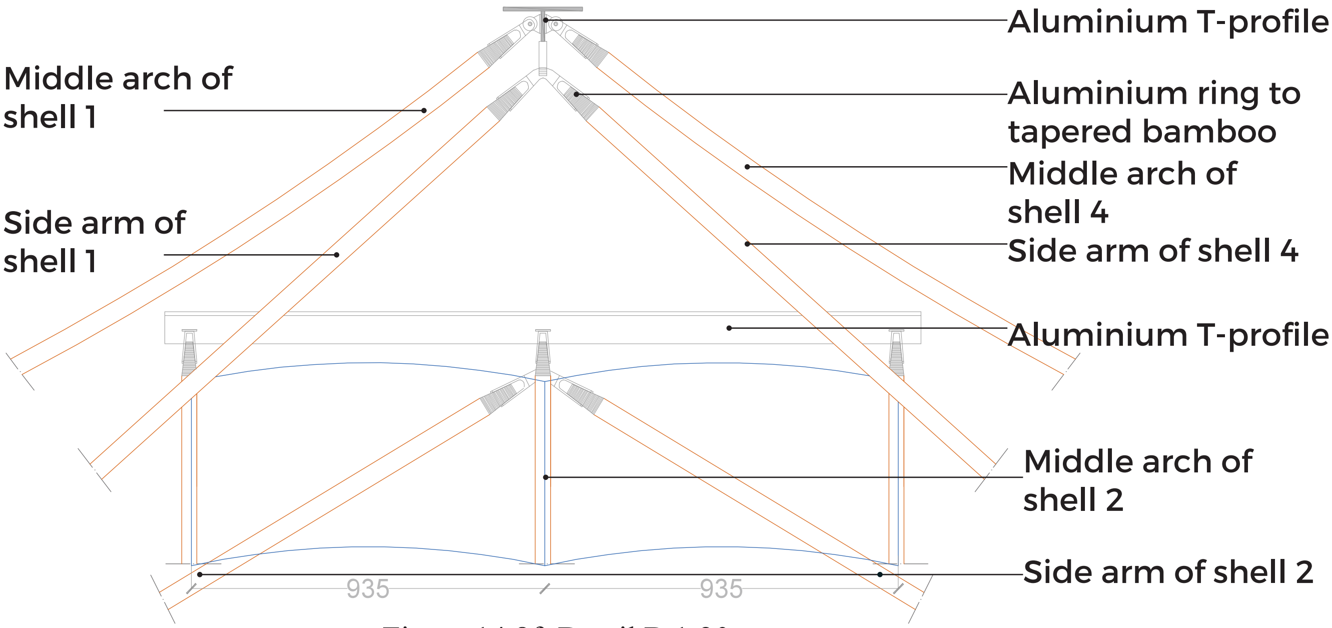


Figure 14.8f: Detail B 1:20

Figure 14.8g: Bamboo x-joint (Val, 2011).

Figure 14.8h: Bamboo-bamboo grid connection(unknown).

BUCKLING ANALYSIS OF BAMBOO

15

15.1 ASSEMBLY SEQUENCE

The main element of the bamboo gridshell is the middle arch, as all the other bamboo elements are resting on this arch (figure 15.1a). Side arms, which are cantilevering are then constructed. The middle concave arch behaves as a tying member and connects the side arms to the main middle arch (figure 15.1b). After the base is constructed, concave and convex parabolic curved elements are assembled. The top most layer consists a single stem bamboo concave parabolic rib. This layer has single stem as it has to be clamped and attached to thin glass. Clamping bundle of bamboo stems together will be difficult. The other layers are bundles to together according to the stiffness required.

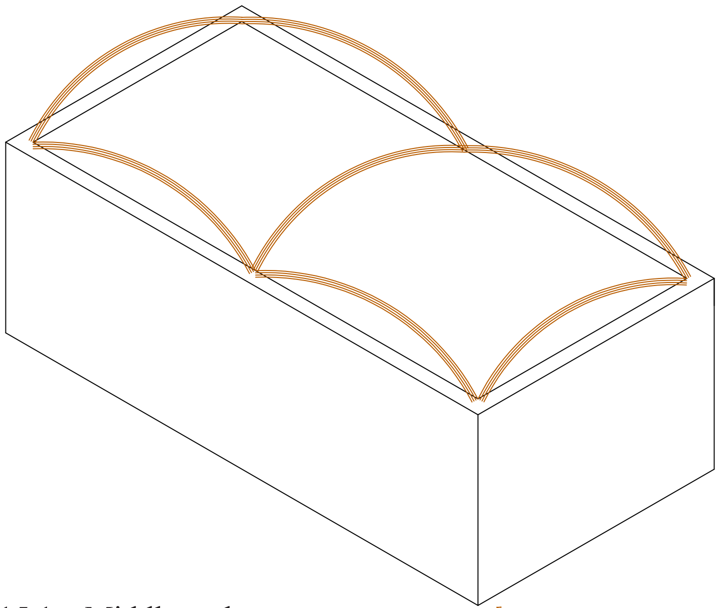


Figure 15.1a: Middle arch

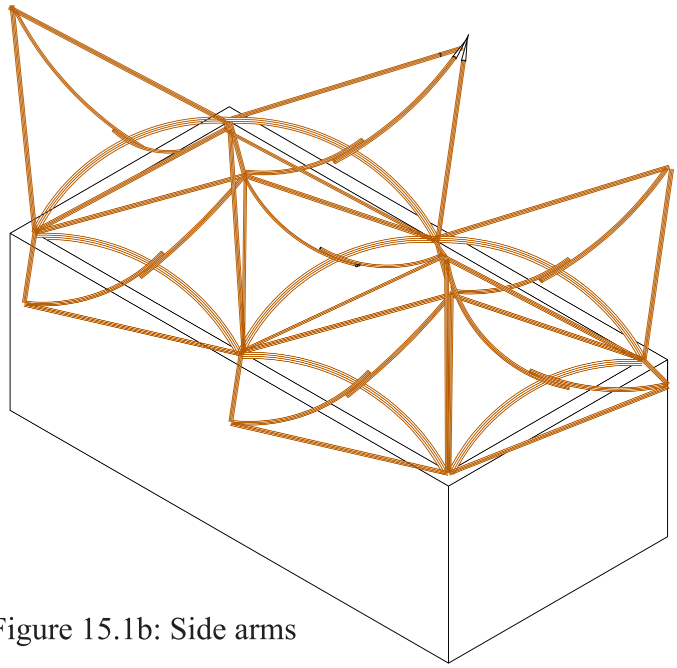


Figure 15.1b: Side arms

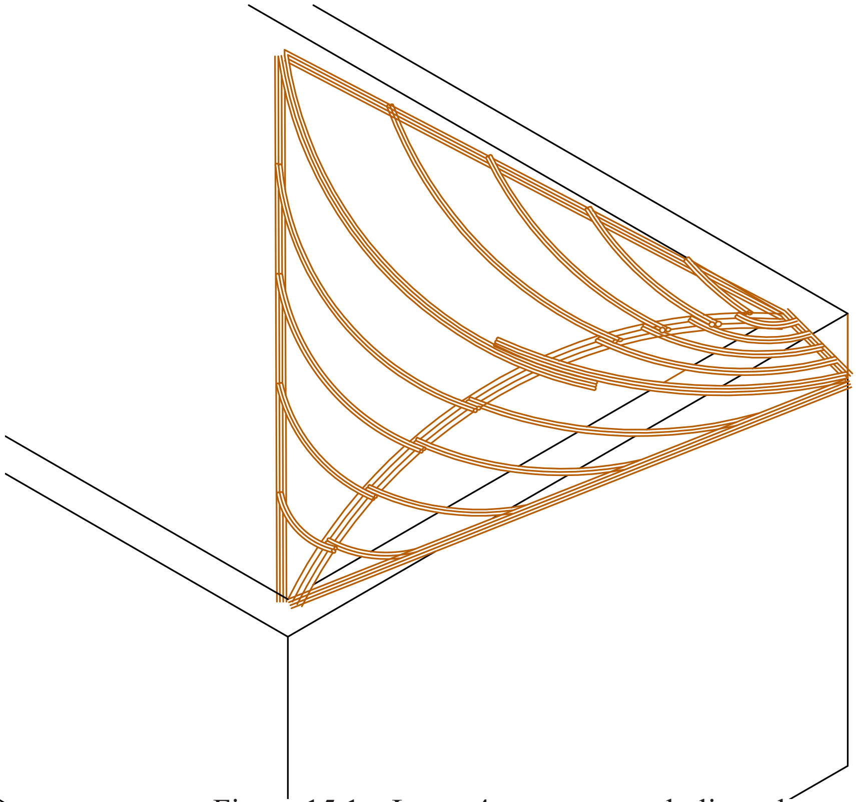


Figure 15.1c: Layer 4 concave parabolic arch

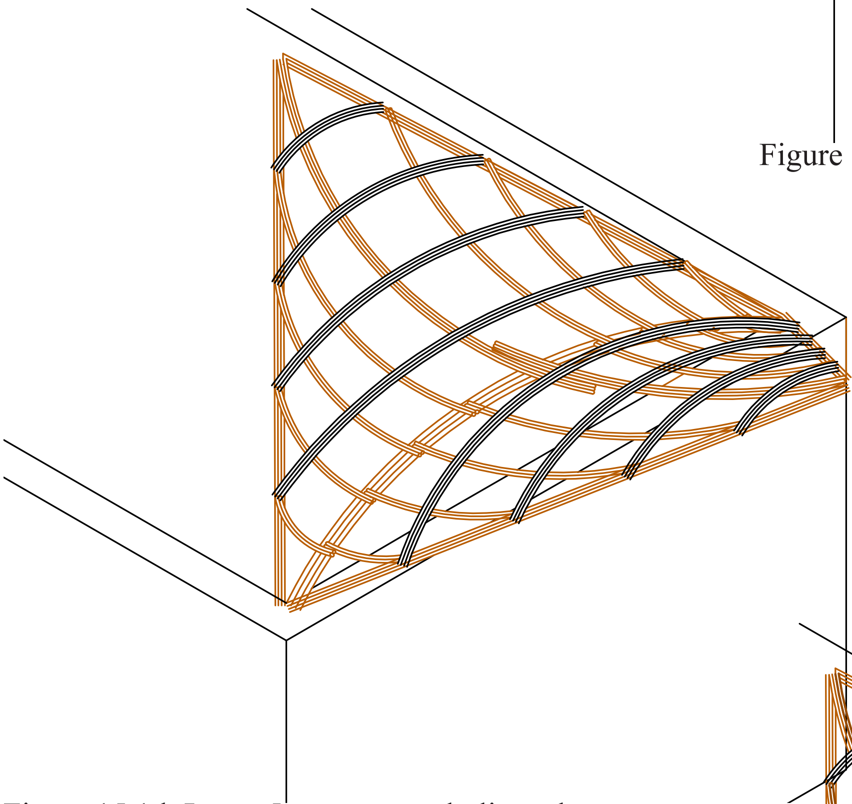


Figure 15.1d: Layer 5 convex parabolic arch

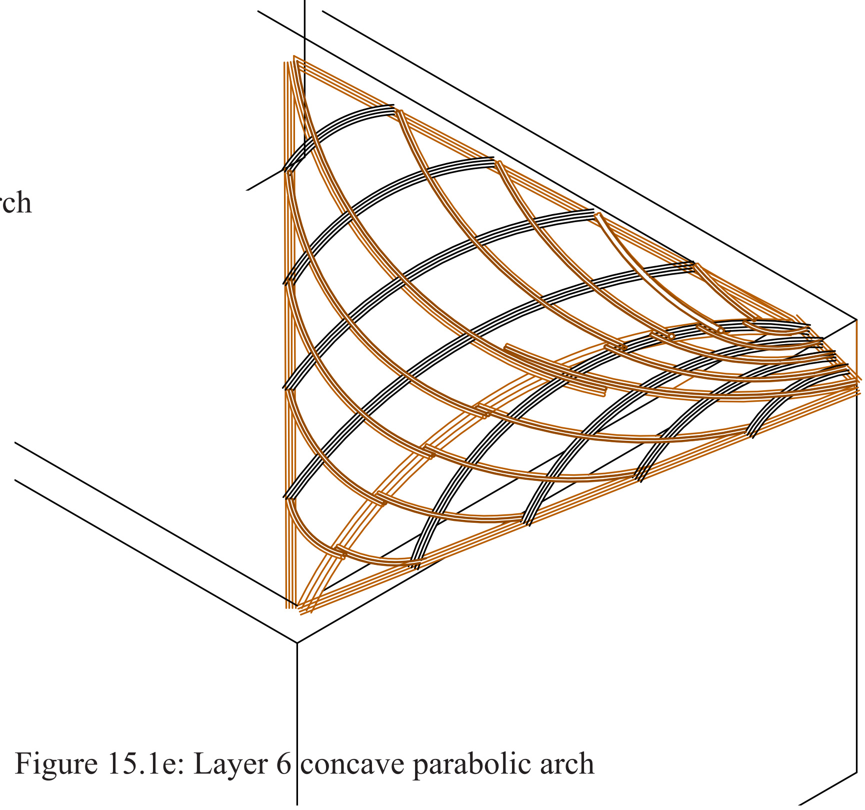


Figure 15.1e: Layer 6 concave parabolic arch

15.2 FAILURE CRITERIA

Natural material like wood and bamboo undergoes viscoelastic deformation. When bamboo is subjected to a load, the deformation increases with time. This effect is described in section 11 and is commonly known as creep behaviour. Most of the deformation is recovered when the load is removed. In an arch, forces are carried mainly through compression and bending is minimum. As slender bamboo poles are used for the construction of the gridshell, instability of these elements needs to be addressed. Instability will lead to buckling and lateral torsional buckling when the structure is under axial compressive or transverse loading. The structure will fail due to buckling before reaching its ultimate strength in this case.

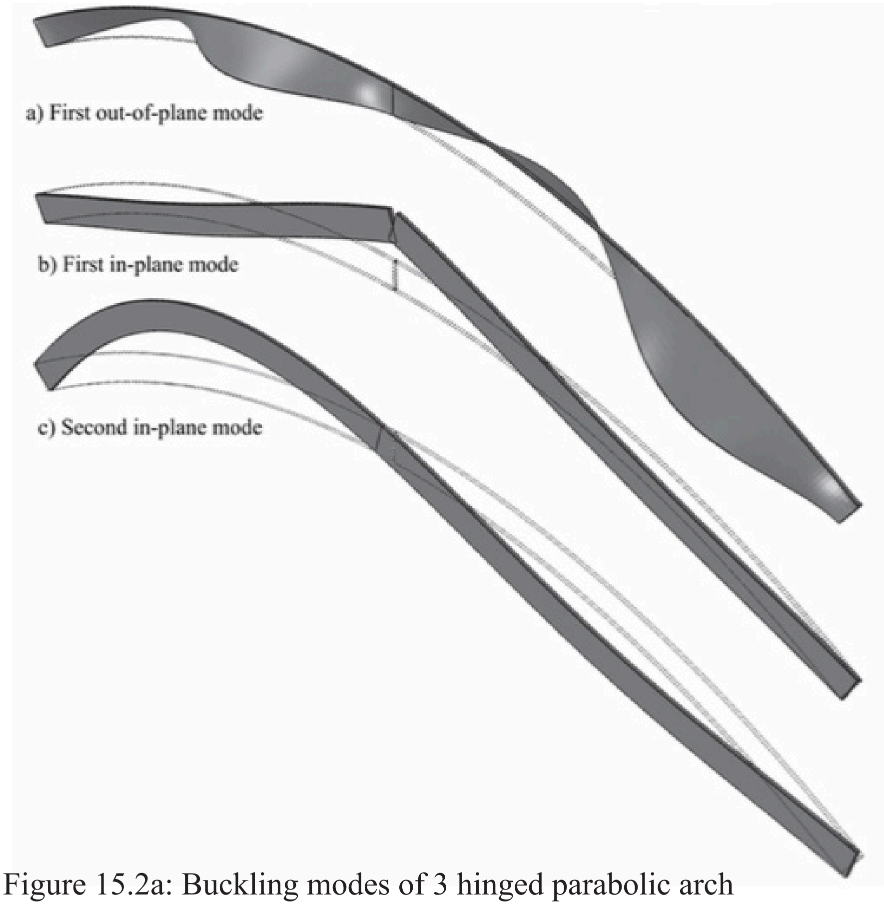


Figure 15.2a: Buckling modes of 3 hinged parabolic arch
ref: (Bjorn Andersson and Gustaf Larsson)

15.3 BUCKLING OF ARCHES

Like slender columns, Arches constructed out of slender members also undergoes buckling. Once the unstable condition of the member is reached, it will buckle due to small disturbances causing large in-plane deformations. The first in-plane buckling mode is represented in figure 15.2b. The members will be exposed to axial and lateral loads simultaneously. The lateral loads will cause eccentricity for the axial loading (Bjorn Andersson and Gustaf Larsson).

Stability analysis using 2nd order theory also known as linear buckling analysis is done in order to know the required stiffness of the structure. (figure 15.2c). Critical load or the maximum load the structure can withstand is determined analytically using the formula given in figure 15.2c. Based on the critical load, the pre-bent arched elements require equivalent stiffness. The members can be made stiff by using large diameters. But this makes the structure bulky and is not practical to use. Even bending of thicker and larger diameter bamboo is not possible (section 11). Hence bamboo of 4cm diameter is used and the stiffness is achieved by bundling a number of bamboo stems together (section 15.4)

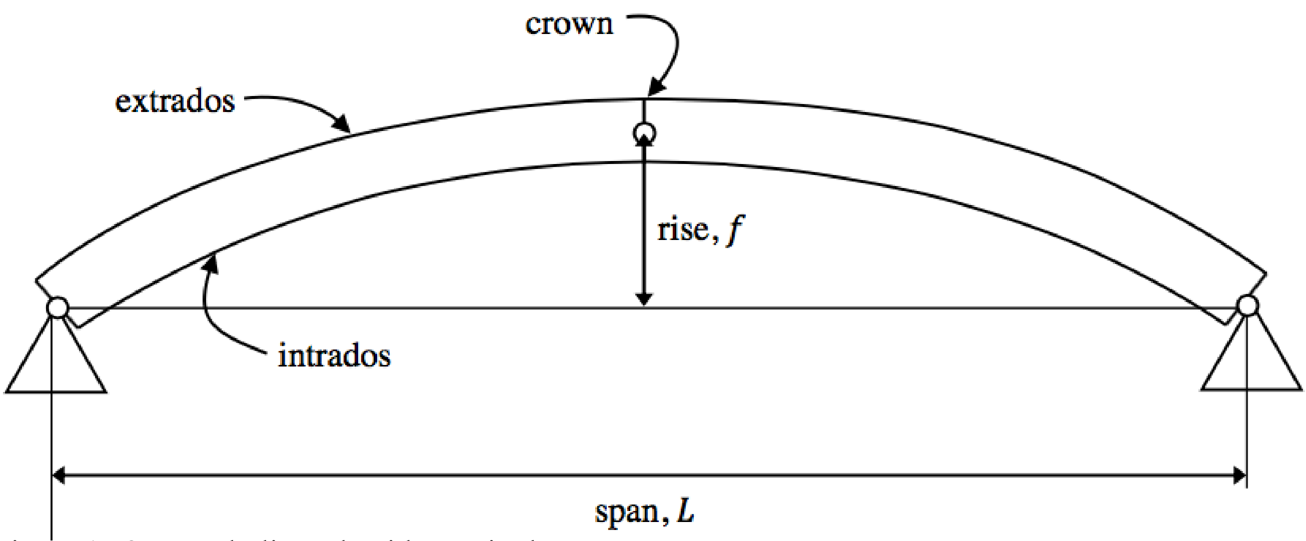


Figure 15.2a: Parabolic arch with terminology.
ref: (Bjorn Andersson and Gustaf Larsson.)

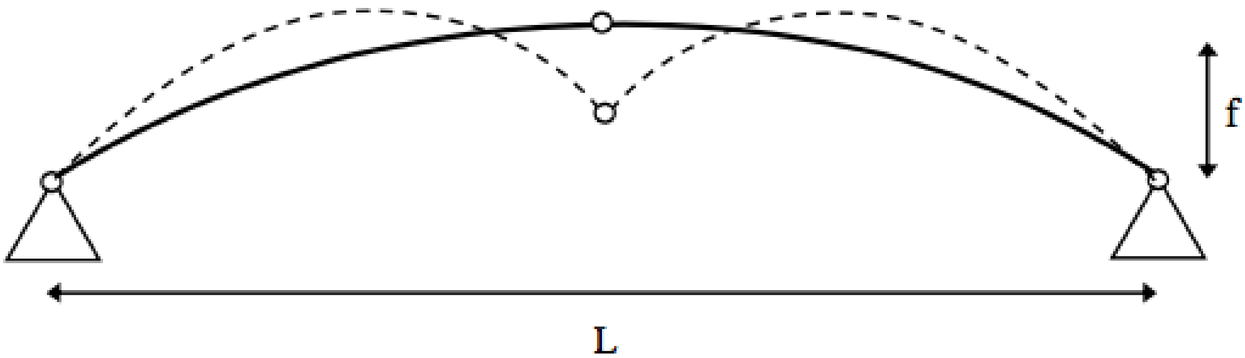


Figure 15.2b: First in-plane buckling mode of 3 hinged parabolic arch
ref: (Bjorn Andersson and Gustaf Larsson.)

Critical load under uniform loading :
(Timoshenko and Gere, 1961)

$$q_{cr} = \gamma_4 \frac{EI}{L^3}$$

where,
EI - bending stiffness of the arch.
L - span

ϒ- numerical factor depending on ratio f/L and no. of hinge connections.

Figure 15.2c: Critical load for first in-plane buckling mode

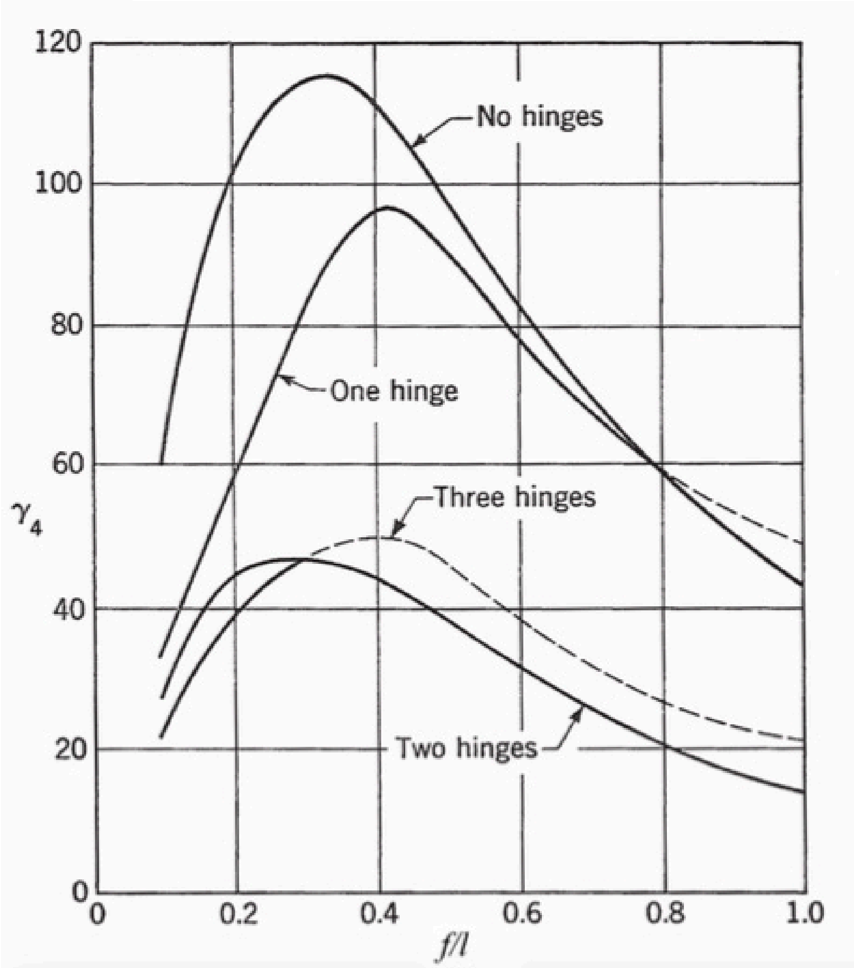


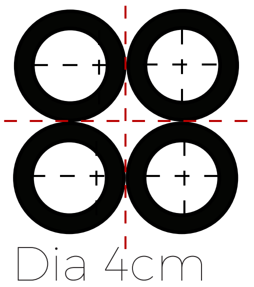
Figure 15.2d: Numerical factor for in plane buckling.

Depending on the boundary condition of the arch, numerical factor needs to be considered. This numerical factor is dependent on the ratio of rise of the arch and its span f/l, and number of hinges used to connect the arch (figure 15.2d). For the roof gridshell structure, a single arch is formed by connecting two pre-bent bamboo poles. The maximum length of the arch is 11.22m. Sometimes bamboo poles of this length might not be available. Even if it is, the end will be tapering and the strength is not consistent. Hence a three hinged arch is considered in this case, where it will be connected at two ends and center (figure 15.2a).

For calculating and optimizing the number of stems, stiffness of each layer is considered. To resist from buckling failure, the total load or force acting on one stem of one layer is compared with the critical buckling force based on the formula (figure 15.2c). This critical force is distributed by 'x' number of stems tied together. The number of stems bundled together is different for each layer as the load on each layer is different. If the number of stems required in a bundle were more than 6, then the stiffness was increased by increasing the diameter size of the bamboo. Hence optimization for each layer was not only in terms of number of stems but also the size of bamboo. For a layer, only one arch was considered with maximum length. The types of loads considered while calculating were self weight, dead load, wind and snow load. SLS was taken into account. The properties of bamboo used for this analytical calculation is taken from the research study of Khatry & Mishra, 2012 (figure 11.2i).

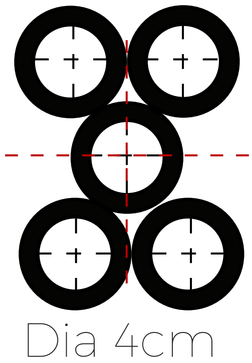
15.4 LAYER OPTIMIZATION

LAYER 6



LAYER 5

Total force (layer6+self-weight+wind+snow) = 369.69N/m
Critical load = 93.39N/m



LAYER 4

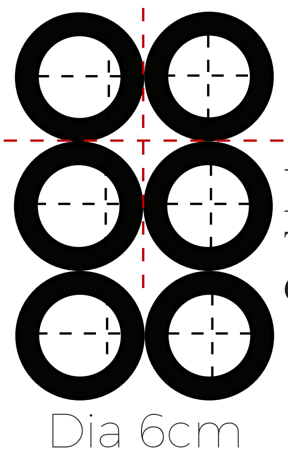
Total force (layer6+layer5+self-weight+wind+snow) = 477.93N/m

Critical load = 118.83N/m

SIDE ARMS

Total force (layer6+layer5+layer4+self-weight+wind+snow) = 579.73N/m

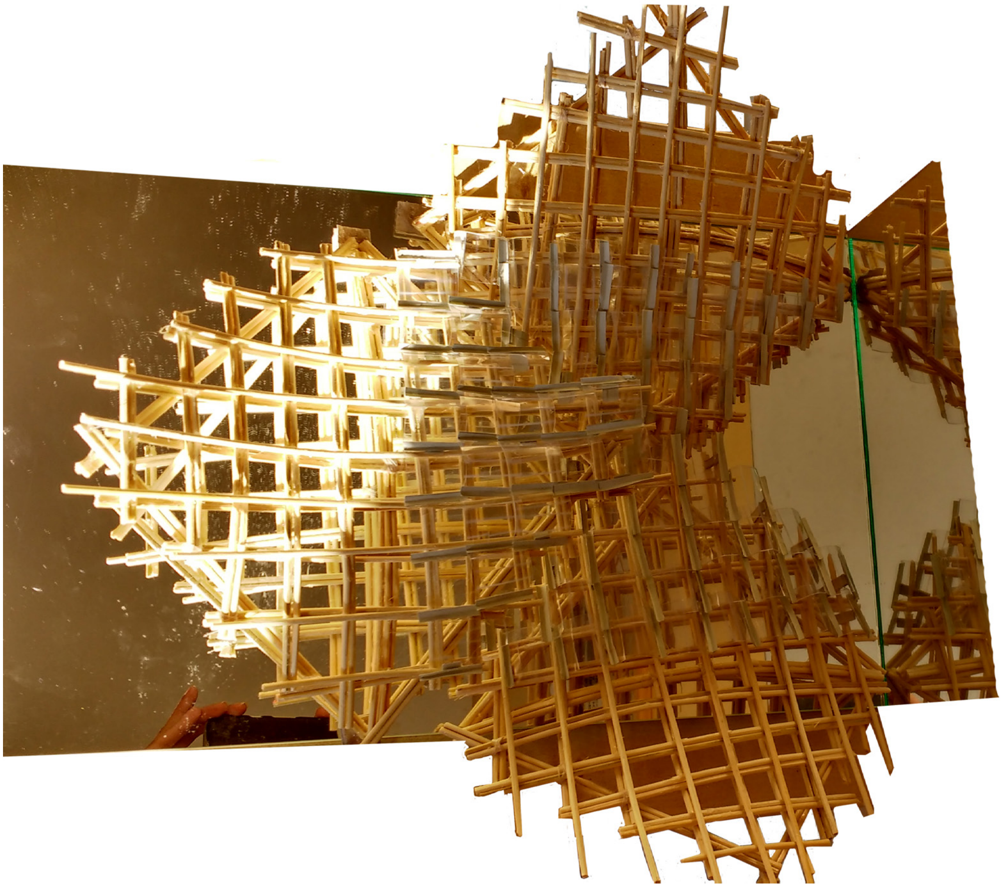
Critical load = 597.84N/m

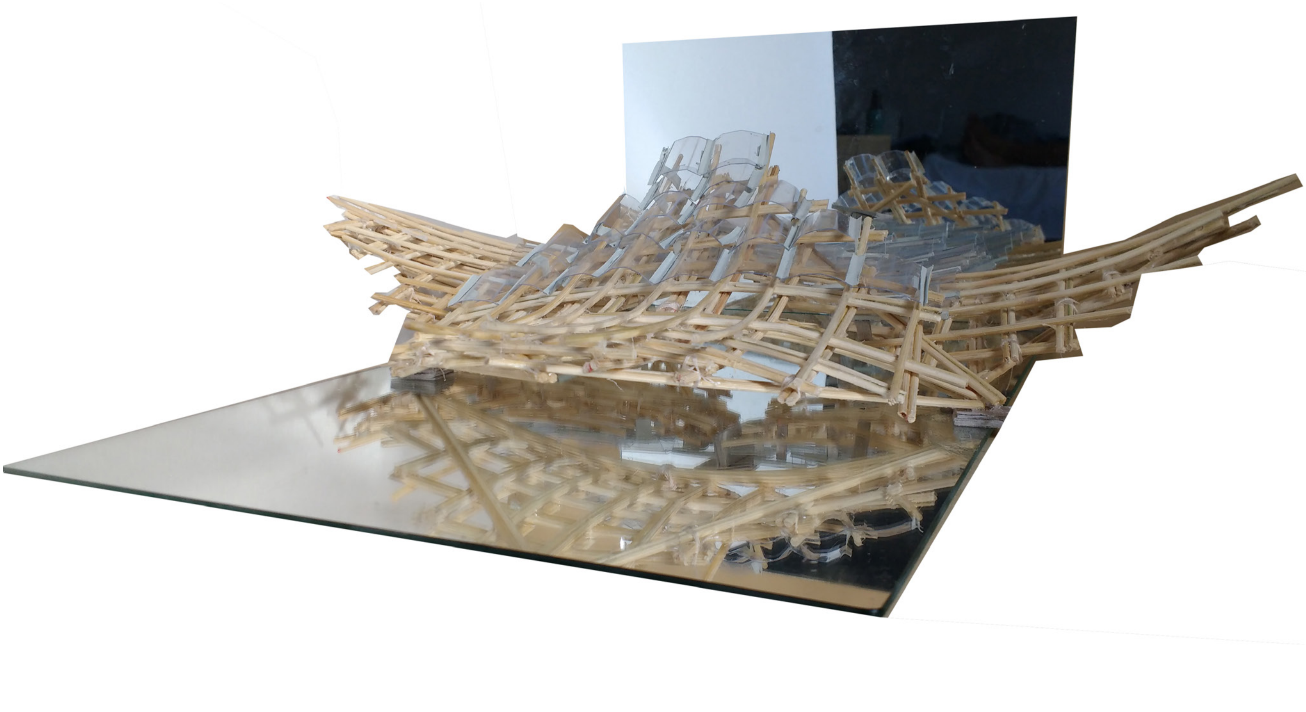


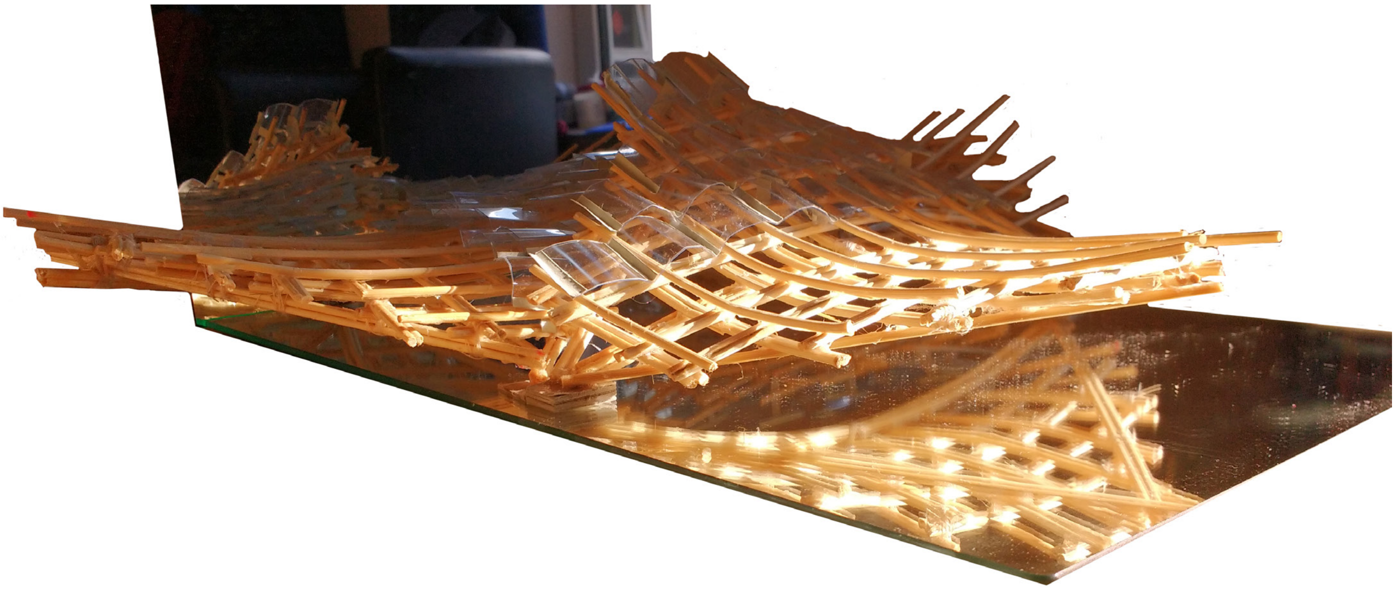
MIDDLE ARCH

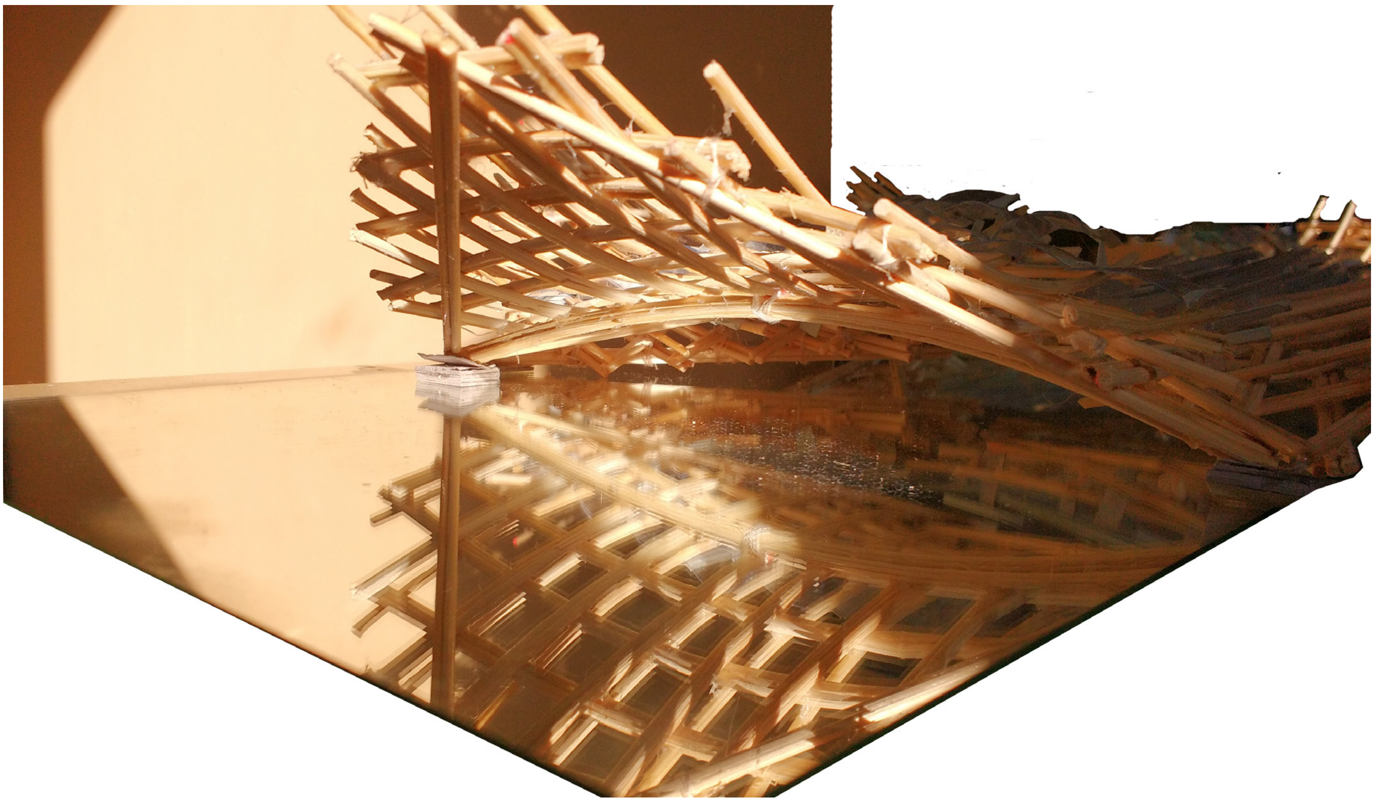
Total force (layer6+layer5+layer4+self-weight+wind+snow) = 2175.19N/m
Critical load = 375.23N/m

MODEL PICTURES 1:50









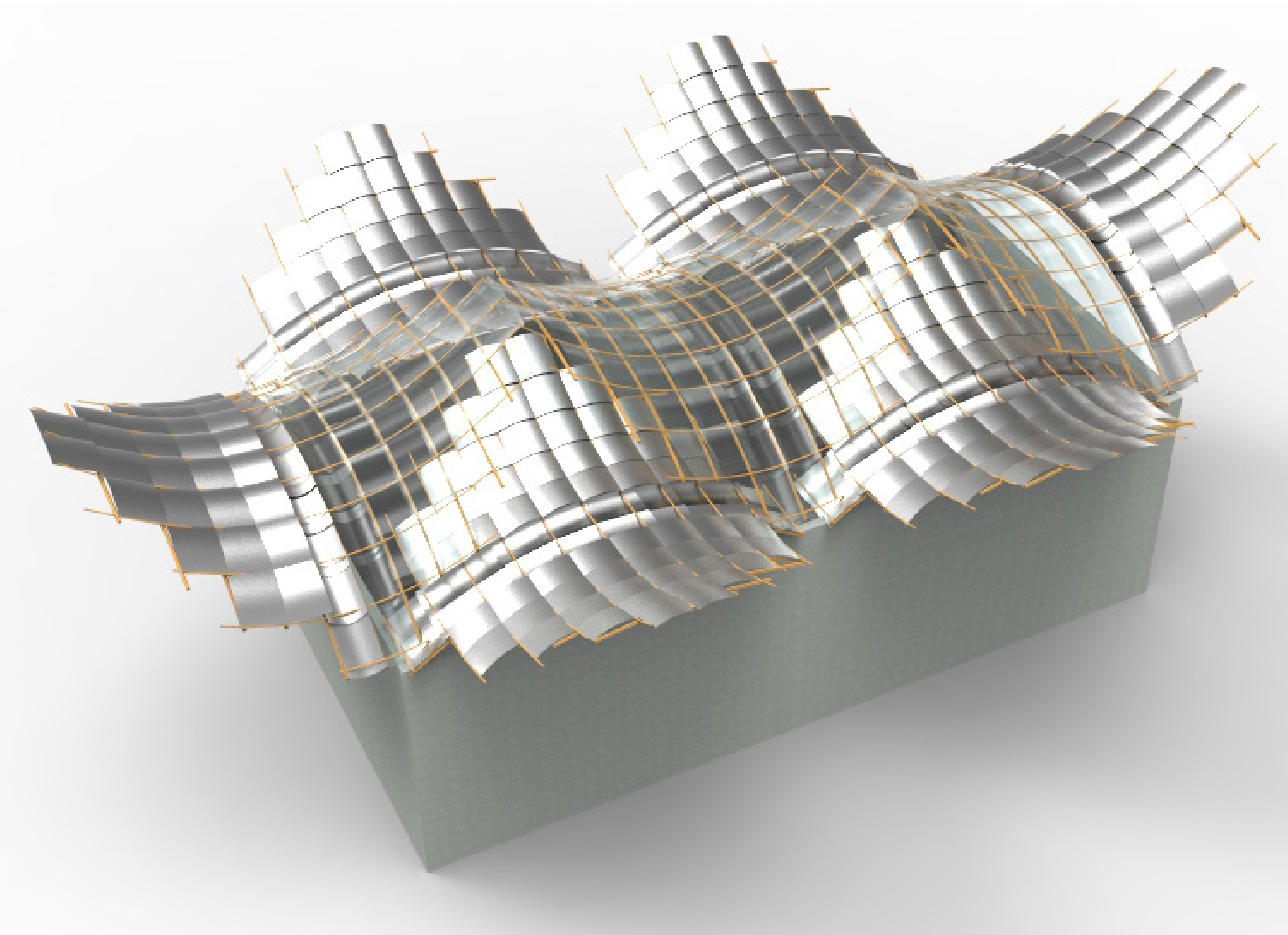
ALTERNATIVES

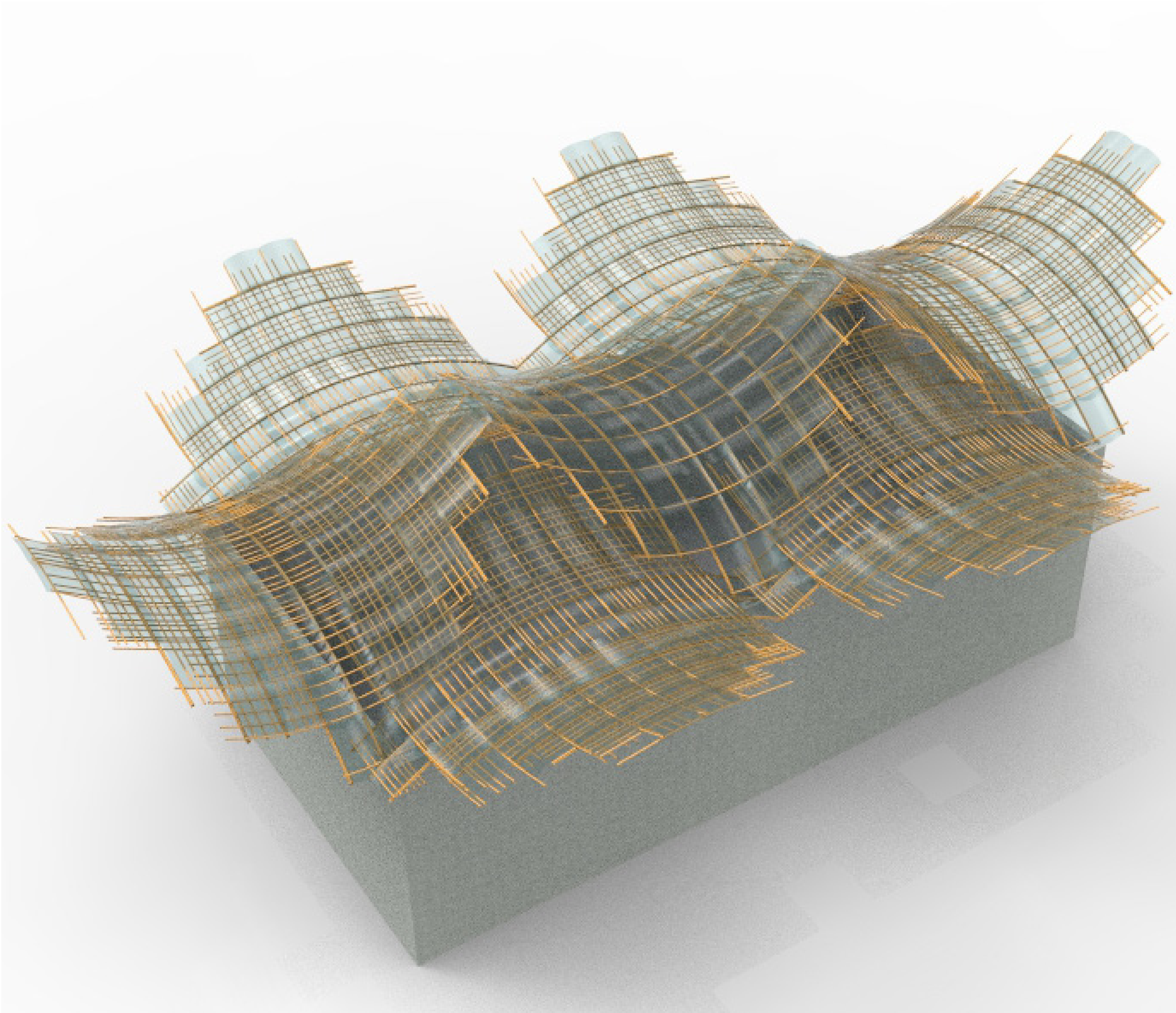
16

16.1 CLADDING MATERIALS

The same technique of cladding can be done with materials. For example aluminium can be deformed into cylindrical curve and overlapped. Like thin glass, the panels can be cold bent on site to adjust with the bamboo structure. Even wooden panels can be suitable and cold bent on site. But pre-bent panels like composites will not be work on this case when tolerances are significant. If there is precision obtained in gridshell, by using steel or wood then pre-bent insulated panels or composites can also be used.

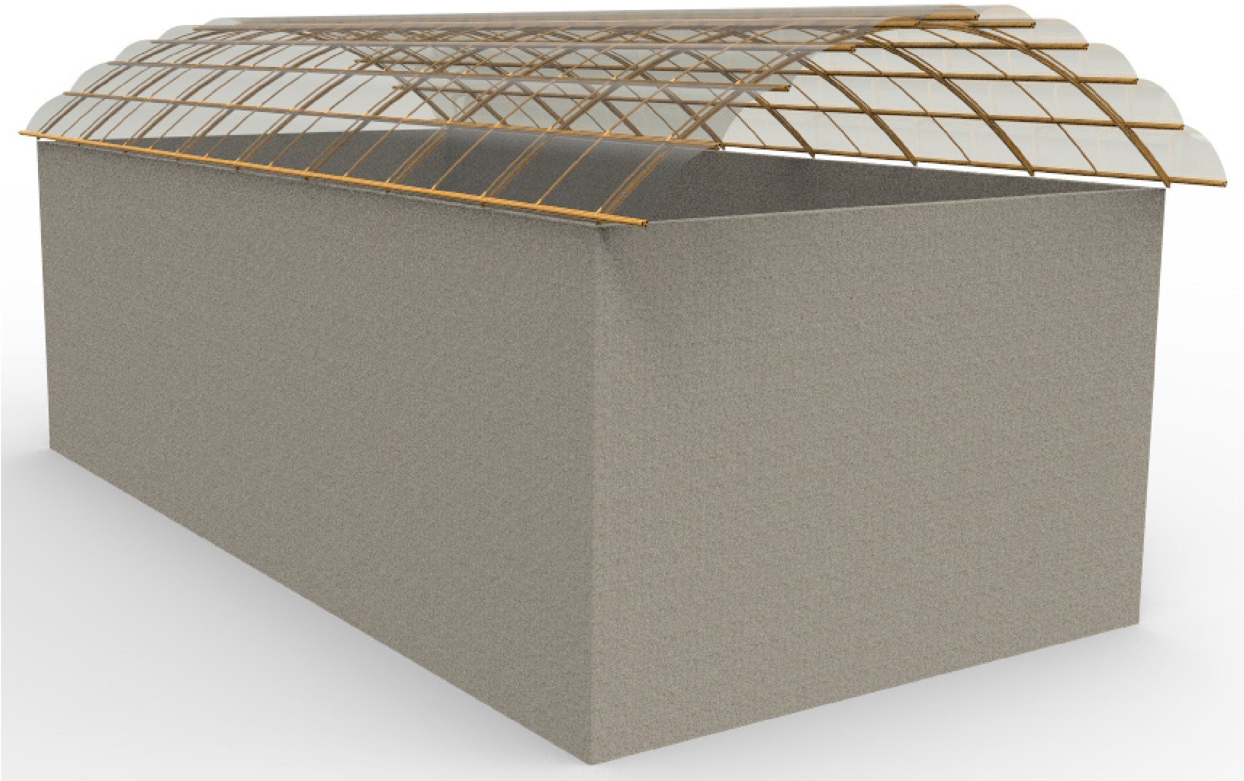
When glass is used as a cladding material, depending on the location, additional insulation might be needed. One option is to partly cover the roof with aluminium and partly with glass to block extra light and heat. The other option is to use bamboo as insulation. Bamboo can be weaved in to a net using splint bamboo canes. The density on the weave can depend on the amount of light that should be filtered inside the structure. Bamboo acts as a good insulation and any other materials do not dominate the bamboo structure.

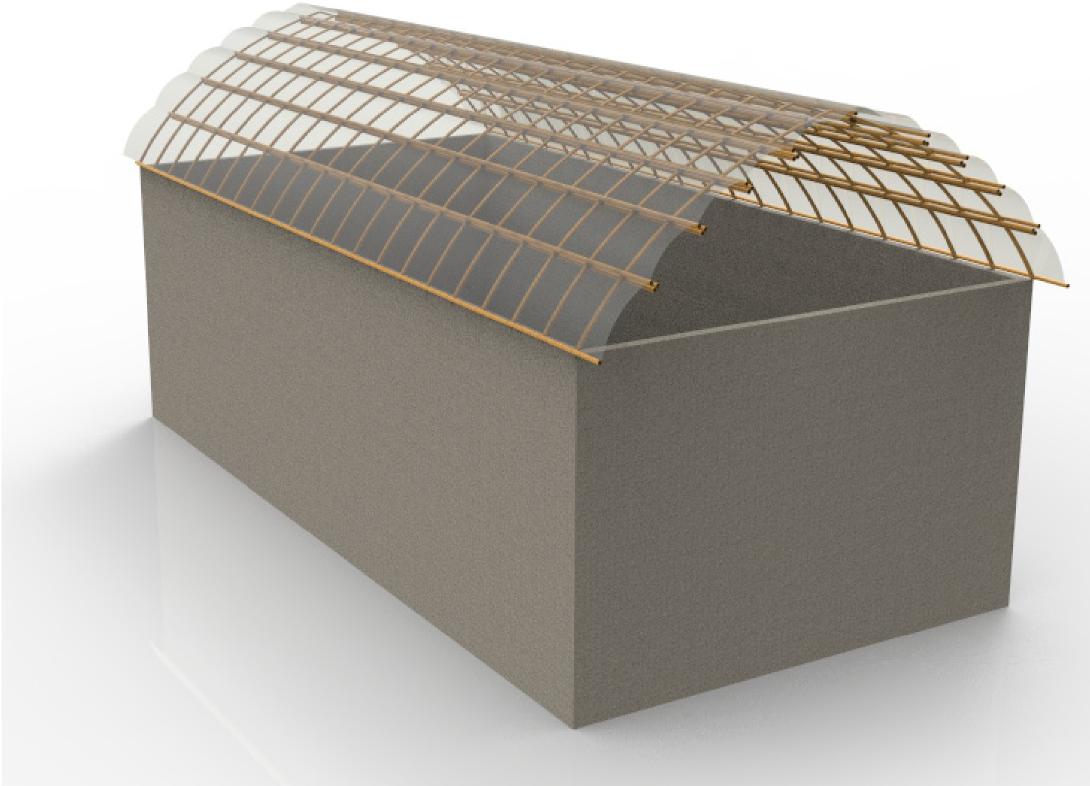


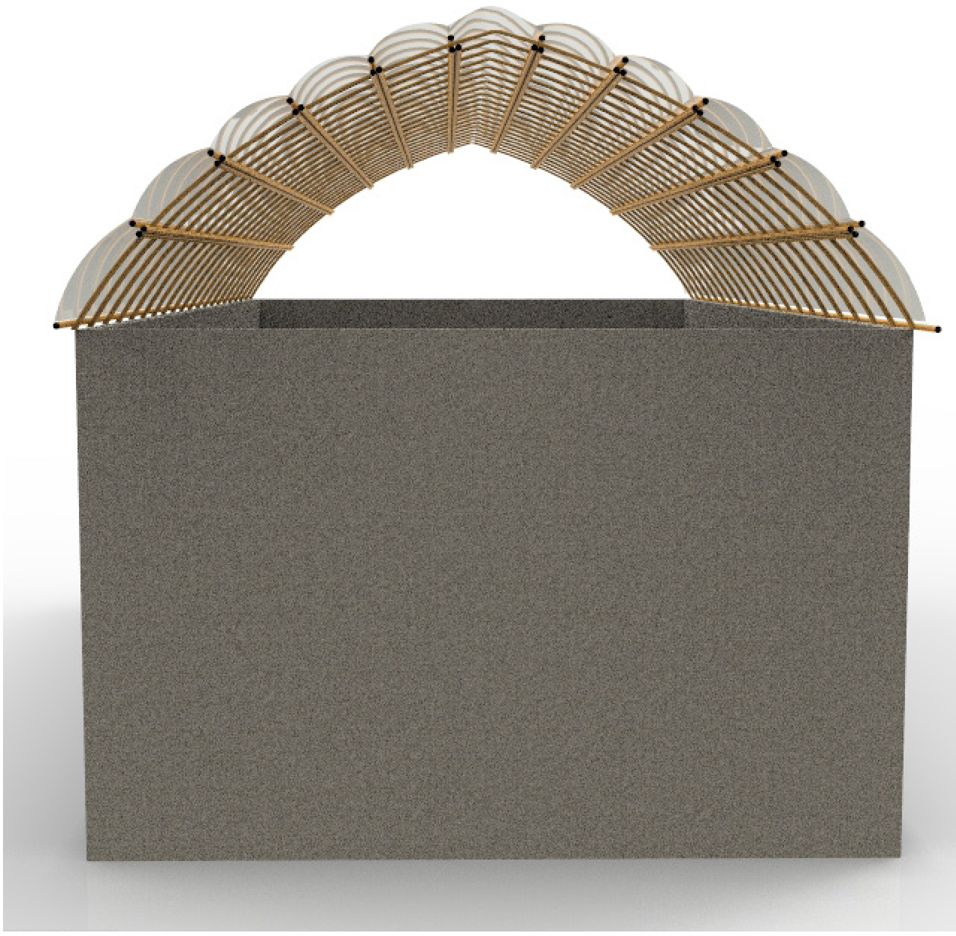


16.2 GEOMETRY AND FORM

This combination of bamboo and thin glass can be used for roof or canopy structure. In terms of geometry there are a number of possibilities. Bamboo can be bent to form cylindrical dome structure or a vault structure. These forms are easier to construct and plan compared to hyperbolic paraboloid but the cantilever part of the hyapr shell protects the structure from rain. If the dome or vault structure is extended out then the cantilever part is not stiff comparatively. Depending on the requirements of the structure based on use and climatic conditions; appropriate form needs to be considered.







CONCLUSIONS AND FUTURE WORK

17

17.1 CONCLUSION

For this master's project the structural feasibility of gridshell, made up of bamboo and thin glass is investigated. The main challenge of this project was to deal with irregularities of bamboo and integrate it with thin glass. In order to increase performance and expand application opportunities, hybridization of traditional material with advanced materials is the approach taken for the research. Structural behaviour when bending bamboo and thin glass is the focus of the study.

The roof of the warehouse is composed of 7 hypar shell elements. The shells are segmented to form parabolic arches. The advantage of using hypar shell is, it does not enclose the structure completely, allowing ventilation and the cantilever part protects the bamboo skeletal structure from rain. Additionally, the segmented bamboo ribs, forming the grid are all of the same nature (parabolic), having same curvature. The inclination of the roof was optimized, based on bending experiments of bamboo. The maximum curvature obtained by bending bamboo was less than the curvature required in the original design. Hence design alteration was required after experiments.

Thin glass as a cladding material behaved perfectly to integrate with bamboo structure. The weight of the structure is maintained low because of this cladding material. The flexibility of thin glass is used to overcome tolerances which are significantly high when constructing with bamboo. Other flexible material like tensile fabric, would not have given the same kind of qualities like stiffness, optical transparency and thermal resistance as thin glass. As thin glass is cold bent, it gives additional stiffness compared to a flat sheet of glass panel. But the curvature at which the glass is bent is governed by the bamboo grid. Bending behaviour of glass to obtain maximum curvature was analyzed using FEM. Thin glass is capable to take care of tolerances up to plus or minus 4.5-5cm. A total of 10cm adjustment might be required as tolerances, when dealing with bamboo for construction. The bamboo gridshell will have to be constructed accurately because of cladding constraints. This accuracy is dependent on bamboo quality and size which should not differ much. It will also be dependent on bending the bamboo poles. Accuracy can be achieved in bending as explained in section 11.4.

The connection between bamboo and thin glass was carefully engineered based on the capabilities and drawbacks of both the materials. To avoid splitting bamboo was clamped and then connected to glass, instead of bolting it. Laminated glass panels were also clamped on two parallel sides, using aluminium reinforcement which was sandwiched between two layers of glass. This provides high tensile connection between glass and metal clamps. The joinery was developed, based on movements and rotations required which is dependent on tolerances. Vertical movement is required when bamboo and thin glass is assembled together. These movements are provided in the clamp that is connected to bamboo.

Thus a natural material, bamboo is combined with high tech material thin glass to increase the performance of bamboo as a structural material.

BAMBOO + THIN GLASS CONSTRUCTION
FOR TROPICAL CLIMATIC CONDITIONS

- DURABLE
  - Choice of material for cladding
  - Choice of material for connections
  - Connection detail
- THIN GLASS overcoming drawbacks of bamboo in terms of construction
- BAMBOO is natural and local material.
- LIGHT WEIGHT STRUCTURE
- ORGANIC FREE FORM GEOMETRY
- WATERPROOF SYSTEM
- ALLOWING NATURAL DAYLIGHT
- ONE MODULE
  Same size module repeated throughout the structure.

- ACCURACY
  More accuracy required while constructing main bamboo structure.
- CAREFUL PLANNING
  Detailing and understanding limitations of both the materials at design stage.
- THIN GLASS is expensive and needs to be imported.
- EXCESS THERMAL GAIN
  Due to glass cladding
- NO INSULATION

17.2 FUTURE RECOMMENDATION

- Non-linear FEA was performed on thin glass to understand the bending behaviour of the material. The results of FEA should be verified by experimenting with cold bent thin glass. Maximum curvature obtained by FEM, should match the maximum curvature obtained by experiments.

- When determining panel size and thickness only symmetrical thickness of glass was considered like 1-0.38-1, 0.56-0.38-0.56, 2-0.38-2. According to few research study, asymmetrical glass performs better in achieving greater maximum curvature and hence should be analyzed.

- A basic linear buckling analytical calculation is done to determine number of bamboo stems needed for the gridshell. However non-linear material property and geometrical non-linearity properties of bamboo should be considered.

- As mentioned in section 11.4, 4-point flexural test will bend a thicker bamboo to a greater extent before yielding. This should be verified through experiments.

- The specimens selected for bending experiments should have length greater than 30D in order to have full flexural capacity.

- The type of bamboo, moisture content, ultimate limit strength of that particular species should also be determined and be included in the experiments.

- More exploration in terms of material for joinery is required based on the forces it needs to resist. Although aluminium will work perfectly, polymers like PVC may prove to be lighter in weight and efficient.

- The overall connection should be tested for joint embedment.

- Metal reinforced laminated in glass can be replaced by polymer fabric like Teflon, if the fabric does not melt in the lamination process. Hence further research is required to understand the lamination process and material property of polymers.

- The performance of the roof in terms of interior climate needs to be evaluated. If required the roof might need additional cladding materials to protect from excess light and heating.

ANSWERS TO RESEARCH QUESTIONS

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- What kind of connections and detailing between thin glass and bamboo is required to serve as durable roof structure?

- The glass envelope protects bamboo from rains. To connect bamboo with glass, mechanical fixtures are used, which are long lasting compared connections done by ropes and bolts.

- How to deal with tolerances on site in terms of joinery detail?

- In horizontal directions the tolerance is solved by overlapping glass to each other and by bend ing the glass according to the bamboo grid. In the vertical direction the mechanical fixtures helps to adjust the panels. Because of the flexibility of thin glass, 4.5-5cm of tolerance can be accommodated.

- Can one size of thin glass module be used to clad the roof?

- Yes. Generally, when organic structure is designed, cladding panels of different size and shapes are used. This proves to be uneconomical. As thin glass is used in this case, the curvature of the glass is dependent on the bamboo grid and adjusts accordingly.

- What factors should be considered to develop a free form bamboo and thin glass gridshell structure?

- Thin glass is bent elastically and bamboo undergoes spring back deflection. To maintain the curvature of thin glass, it is clamped using metal reinforcement. Whereas, bamboo should be bent extra to have close approximation of the desired curve.

- What is the maximum curvature that can be obtained for bamboo and thin glass?

- Bamboo - 1.1m for diameter of 2cm and 11.11m for diameter of 5cm. The curvature obtained from 5cm is less than required. Hence bamboo of smaller diameter is used.

- In the most precise and standard case when the distance between the bamboo grid is 935mm, the curvature of the glass panel will be 0.73m. But when the bamboo grid is shifted and be comes closer by 5cm i.e. 885mm, then the glass will be curved maximum to a radius of 0.55mm. And if the grid is shifted away by 5cm and the distance between two bamboo becomes 985mm, then glass has minimum curvature of 1.2m.

- What is the spring back deflection while bending bamboo?

- Bamboo spring backs to its original position by 70%-73% if kept in fixed position for 30-45 minutes.

- Is it possible to bend bamboo to some extra amount so that it spring backs to the curvature desired?

- Yes it is possible to predict the spring back after experimenting on specimens of same spe cies and size.

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APPENDIX 1

BUCKLING ANALYTICAL CALCULATIONS

LAYER 6 - 12 stems

Density	700	700	700	700	700	700
length	0.65	2.541	4.501	6.576	8.806	11.22
Rout	0.025	0.025	0.025	0.025	0.025	0.025
Rin	0.018	0.018	0.018	0.018	0.018	0.018
Volume	0.000614341	0.002401601	0.00425408	0.00621524	0.0083229	0.01060447
Mass	0.4300387	1.681120518	2.9778526	4.35066845	5.82603199	7.42312956
No. of bamboo	1	1	1	1	1	1
force	4.21437926	16.47498108	29.1829555	42.6365508	57.0951135	72.7466697
force/meter	6.4836604	6.4836604	6.4836604	6.4836604	6.4836604	6.4836604
safety factor	7.78039248	7.78039248	7.78039248	7.78039248	7.78039248	7.78039248
load distributed per stem	7.78039248	2.59346416	1.5560785	0.97254906	0.86448805	0.70730841

LAYER 5 - 11 STEMS

Density	700	700	700	700	700	700
length	1.807	3.557	5.384	7.32	9.394	11.22
Rout	0.02	0.02	0.02	0.02	0.02	0.02
Rin	0.014	0.014	0.014	0.014	0.014	0.014
Volume	0.001157492	0.002278472	0.00344878	0.0046889	0.00601742	0.00718708
Mass	0.810244344	1.594930344	2.41414253	3.28222944	4.21219445	5.03095824
No. of bamboo	4	4	4	4	4	4
force	31.76157828	62.52126948	94.6343871	128.663394	165.118022	197.213563
force/meter	17.5769664	17.5769664	17.5769664	17.5769664	17.5769664	17.5769664
safety factor	21.09235968	21.09235968	21.0923597	21.0923597	21.0923597	21.0923597
wt. distributed per stem	4.218471936	4.218471936	2.63654496	1.91748724	1.62248921	1.62248921
wind N/m					188.4	
snow N/m					150.72	
total force (selft wt+layer6)					369.691051	

LAYER 4 - 12 stems

Density	700	700	700	700	700	700
length	0.65	2.541	4.501	6.576	8.806	11.22
Rout	0.02	0.02	0.02	0.02	0.02	0.02
Rin	0.014	0.014	0.014	0.014	0.014	0.014
Volume	0.000416364	0.001627663	0.00288316	0.00421232	0.00564077	0.00718708
Mass	0.2914548	1.139364072	2.01821239	2.94862579	3.94853995	5.03095824
No. of bamboo	5	5	5	5	5	5
force	14.2812852	55.82883953	98.8924072	144.482664	193.478458	246.516954
force/meter	21.971208	21.971208	21.971208	21.971208	21.971208	21.971208
safety factor	17.13754224	66.99460743	118.670889	173.379197	232.174149	295.820345
wt. distributed per stem	5.71251408	22.33153581	39.5569629	57.7930655	77.3913831	98.6067815
wind					188.4	
snow					150.72	
total force (selft wt+layer6,5)					477.931853	

BUCKLING ANALYTICAL CALCULATIONS

	R1	R2
Rout	0.02	0.018
Rmiddle	0.018	0.016
Rin	0.016	0.014

Eout	17000000000	Iout	4.31938E-08
Emiddle	16000000000	Imiddle	3.09604E-08
Ein	12000000000	Iin	2.12892E-08

EItotal 1485.13208

LAYER 5

qcr n. EI/L^3

f	1.664
l	8.6
f/l	0.193488372
n	40
L	8.6
qcr	93.39630976

$$q_{cr} = \gamma_4 \frac{EI}{L^3}$$

where,
EI - bending stiffness of the arch.
L - span
ϒ- numerical factor depending on ratio f/L and no. of hinge connections.

LAYER 4

qcr n. EI/L^3

f	2.25
l	8.13
f/l	0.276752768
n	43
L	8.13
qcr	118.8397961

Side arms

Density	700
length	7.07
Rout	0.02
Rin	0.014
Volume	0.004528759
Mass	3.17013144
No. of bamboo	2
force	62.13457622
force/meter	8.7884832
safety factor	74.56149147
wind	188.4
snow	150.72
total force (selft wt+layer6,5,4)	579.7327305

SIDE ARMS

qcr	3.14^2EI/(n*L)^2	
n	0.7	(hinged oe end, other end fixed)
L	7.07	
qcr	597.8461927	

Middle arc

Density	700
length	11.22
Rout	0.03
Rin	0.018
Volume	0.020292941
Mass	14.20505856
No. of bamboo	6
force	835.2574433
force/meter	74.4436224
safety factor	1002.308932
wind	282.6
snow	226.08
total force (selft wt+layer6,5,4)	2175.193888

	R1	R2	
Rout	0.03	0.026	
Rmiddle		0.026	0.022
Rin	0.022	0.018	

Eout	17000000000	Iout	2.77124E-07
Emiddle	16000000000	Imiddle	1.74835E-07
Ein	12000000000	Iin	1.01485E-07
EItotal	8726.28608		

MIDDLE ARC

qcr	n. EI/L^3
f	2.25
l	10
f/l	0.225
n	43
L	10
qcr	375.2303014

APPENDIX 2

CLAMP CALCULATION

Aluminium Density kg/m3	2650
clamp thickness m	0.005
clamp width m	0.05
clamp outer radius m	0.032
clamp inner radius	0.027
volume m3	0.000785
height of plates m	0.075
width of plates m	0.05
thickness of plates m	0.005
volume of plates m3	0.00001875
no. of plates	2
Total volume of clamp	0.0008225
Mass of clamp kg	2.179625

Friction between rubber and bamboo	0.9
Clamping force N	2200
Radius	0.032
Frictional Torque N.m	63.36

Wind load N/m2	1500
wind load on clamp N	5.625
radius	0.107
torque N.m	0.601875

thin glass resistance	333.333333
Wind load N/m2	1500
wind load on clamp N	5.625
radius	0.107
total force	338.958333
torque N.m	36.2685417